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JULY-SEPTEMBER 1987(U) OFFICE OF NAVAL RESEARCH LIAISON
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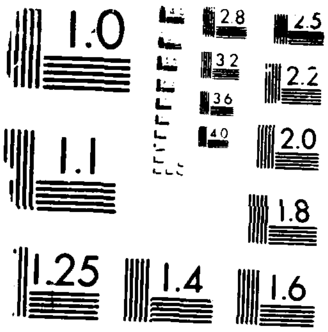

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JULY TO SEPTEMBER 1987 VOL. 12, NO. 3

SCIENTIFIC BULLETIN

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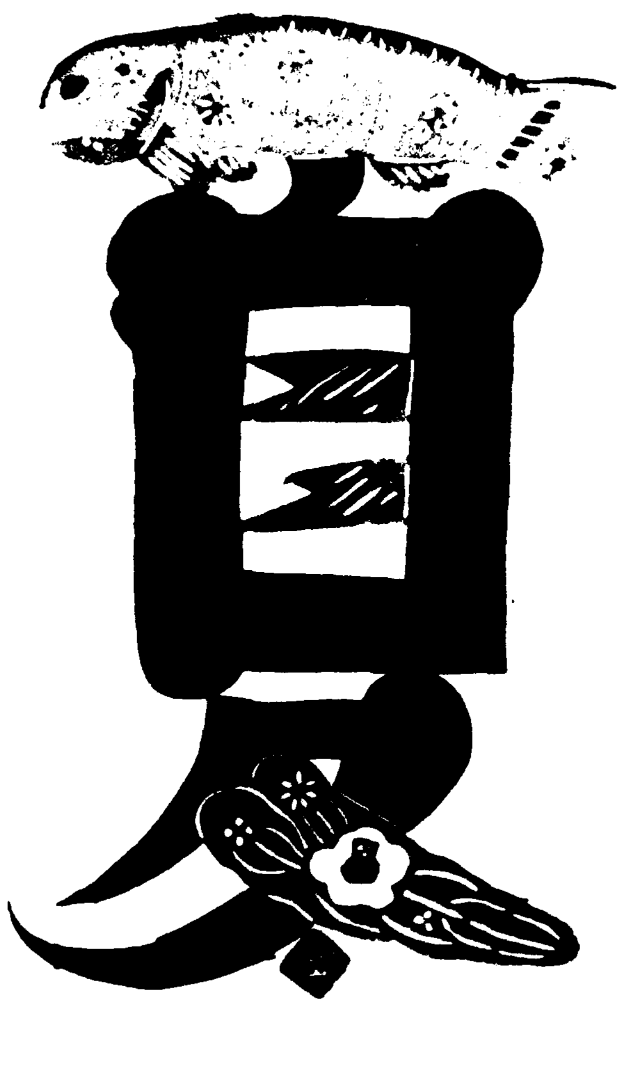

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NAVSO P-3580

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT
APPROVED FOR PUBLIC RELEASE;
DISTRIBUTION UNLIMITED.

4. PERFORMING ORGANIZATION REPORT NUMBER(S)
ONRFE Vol 12, No. 3

5. MONITORING ORGANIZATION REPORT NUMBER(S)

6a. NAME OF PERFORMING ORGANIZATION
ONR/AFOSR/ARO

6b. OFFICE SYMBOL (If applicable)

7a. NAME OF MONITORING ORGANIZATION

6c. ADDRESS (City, State, and ZIP Code)
Liaison Office, Far East
APO San Francisco 96503-0007

7b. ADDRESS (City, State, and ZIP Code)

8a. NAME OF FUNDING / SPONSORING ORGANIZATION

8b. OFFICE SYMBOL (If applicable)

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

8c. ADDRESS (City, State, and ZIP Code)

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO	PROJECT NO	TASK NO	WORK UNIT ACCESSION NO

Accession For
NTIS GRA&I
DTIC TAB
Unannounced
Justification
By
Distribution/
Availability Codes
Dist | Avail and/or Special
A-1

11. TITLE (Include Security Classification)
ONR FAR EAST SCIENTIFIC BULLETIN

12. PERSONAL AUTHOR(S)
George B. Wright, Director; Sandy Kawano, Editor

13a. TYPE OF REPORT

13b. TIME COVERED FROM ______ TO ______

14. DATE OF REPORT (Year, Month, Day)
July-September 1987

15. PAGE COUNT

16. SUPPLEMENTARY NOTATION
ISSN: 0271-7077

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Anodic oxidation, Demagnetization, Wave climate, Japan, India, Wave refraction, Electrodeposition, Marine science, Fracture prevention

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This is a quarterly publication presenting articles covering recent developments in Far Eastern (particularly Japanese) scientific research. It is hoped that these reports (which do not constitute part of the scientific literature) will prove to be of value to scientists by providing items of interest well in advance of the usual scientific publications. The articles are written primarily by members of the staff of ONR Far East, the Air Force Office of Scientific Research, and the Army Research Office, with certain reports also being contributed by visiting stateside scientists. Occasionally, a regional scientist will be invited to submit an article covering his own work, considered to be of special interest.

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20. DISTRIBUTION / AVAILABILITY OF ABSTRACT
☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION

22a. NAME OF RESPONSIBLE INDIVIDUAL

22b. TELEPHONE (Include Area Code)

22c. OFFICE SYMBOL

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

18. Subject Terms (Key Words) continued

Perpendicular magnetic recording
Coastal mineral deposits
Fracture mechanics methodology
Fracture toughness and strength
Static and dynamic fracture
Fatigue behavior
Contact stress effects
Testing methods for structural ceramics
Ceramics
People's Republic of China
Shipbuilding
Hydraulic research and development
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Magneto-optics
Permanent magnets
Taiwan
Materials engineering research facilities
Engineering schools
Steel production
Electron holography
Aharonov-Bohm effect
Flux quantization
Superconductivity

CONTENTS

Cover: This issue features "Summer," the third in a series of four Katazome (stencil dyeing) prints from Kichiemon Okamura's "Four Seasons," an expressive rendering of Kanji characters depicting each season of the year.

ERRATA NOTICE

Please make the following changes to the article titled "The Sixth International Conference on High-Power Particle Beams, BEAMS '86," by M. Kristiansen and A.K. Hyder, which appeared in Vol 12, No. 1, pages 23-26.

Page 23, 2nd column, line 24	Change "linear" to "liner"
Page 24, Footnote	Change to read: "Kristiansen, M., and F. Rose. 1985. Inertial confinement fusion research in Japan. *Scientific Bulletin* 10, no. 2:171-173."
Page 25, 1st column, line 12	Change "planting" to "plating"

PERPENDICULAR MAGNETIC RECORDING BY ANODIC OXIDATION

Noboru Tsuya, Tadeo Tokushima, and Earl Callen

Hard and floppy disks for perpendicular magnetic recording have been prepared by electrodeposition of an alumina film on an aluminum substrate. Micropores, simultaneously etched in the alumina, form a hexagonal array. The pores are of uniform spacing, diameter, and depth, and are perpendicular to the film plane. The pores are widened and filled with iron by electrodeposition. These iron needles are oriented single crystals whose demagnetization field holds the magnetization of the iron closely along the needle axis. Hysteresis curves are rectangular; the coercive force can be adjusted to a technically desirable value, such as 1,000 Oe. Signal to noise is excellent; overwrite modulation is less than -30 dB. Alumina is a hard material, and an SiO_2 covering layer further protects the film. The disks have been exposed to harsh environments and elevated temperatures and run for 1,000 hours, with 30,000 start-stop tests, without evident deterioration.

INTRODUCTION

In magnetic recording magnetostatics gets in the way; the magnetic field of one magnetized region tends to demagnetize and to "talk to" adjacent regions. If one magnetizes a thin iron film, the magnetic moment of each domain will lie in the film plane because such an arrangement reduces magnetostatic energy. This is the planar geometry of longitudinal recording. But because there is interaction between the magnetized regions, either storage density is relatively low or demagnetization and cross-talk high.

Advocates claim that storage density and signal/noise can be improved by a factor of as much as 100 if one can force the magnetization to lie perpendicular to the film plane. This is the idea of perpendicular magnetic recording. One approach is to use the natural desire of the moment in some materials to line up along a particular axis. For example, the moment in Co wants to lie along the c-axis. So if Co can be deposited on the film in crystalline form, with the c-axes vertical, the moment will be normal to the film plane. This is the impetus in Co-Cr films and in most other proposed perpendicular recording systems. A wholly different approach is to use magnetostatics itself to force the moment vertical—to shape individual ferromagnet needles oriented normal to the film plane. But how to do it? And which approach is better?

ANODIC OXIDATION PROCESS

Since the proposal of perpendicular magnetic recording by Iwasaki and Nakamura (Ref 1) some 10 years ago, many systems have been investigated and the race continues to be intense. That race will be won not necessarily by the entry with highest packing density or other technical figure of merit. Such practical considerations as regularity, absence of defects, convenience and cost of manufacture, yield, and robustness against mechanical and environmental degradation are at least as important. A technique that shows high promise on most counts, at least for hard and floppy disks, is that of electrodeposition of ferromagnetic metal in oxidized aluminum. And now the groups at Hosei University and Yamaha Laboratories have made such progress that it seems likely that Yamaha will soon be the first to commercialize perpendicular magnetic recording disks, first hard then floppy disks.

Anodic oxidation is widely used for coating and coloring aluminum. Normally the oxide (alumite or alumina, Al_2O_3) layer grows to a thickness at which electrolysis stops because of electrical insulation by the layer itself. But when a mild acid is added to the electrolyzing bath, cylindrical micropores are formed (Ref 2). While the oxide is growing, the acid is simultaneously etching the pores, allowing electrical conductivity to the aluminum substrate. Layers can be grown to any thickness; the longer electrolysis is continued, the thicker the alumina layer and the deeper the pores. At the bottom of each pore is a thin barrier region, probably an oxide complex. Conductivity presumably occurs through this barrier. Alumite layers from 0.4 μm up to 3 μm have been investigated. Thicker layers have been produced, but for magnetic recording there seems tc be no immediate need for them. The pores are of uniform depth and are reasonably straight, parallel, and vertical to the disk plane.

Nature is beautiful. The pores form a two-dimensional, hexagonal close-packed (honeycomb) lattice (Figure 1). The cell size, D_C, or lattice constant, turns out to be linear in the electrolysis voltage (Ref 3), but for any constant voltage the lattice is fairly uniform, like a short range ordered crystal. Cell sizes between 400 and 1,400 Å are convenient. A cell size of 1,000 Å corresponds to a packing density of 10^{10} bits/cm², beyond individual differentiation with present-day reading and writing equipment.

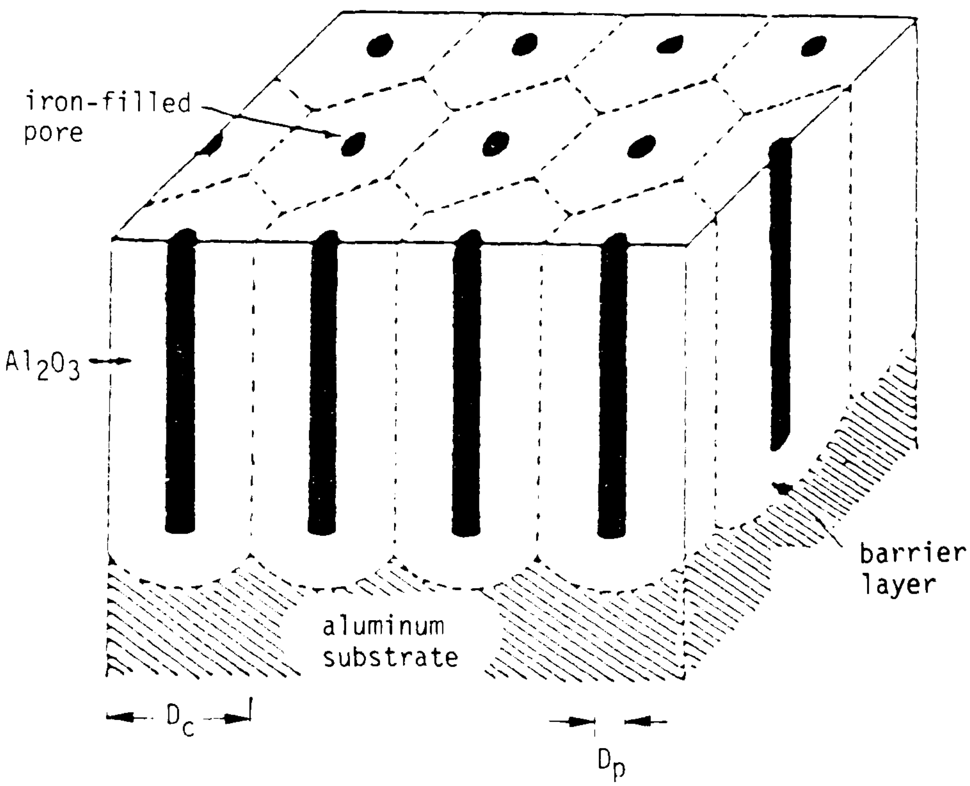

Figure 1. Honeycomb of pores in the oxide layer.

In the commercial coloring of aluminum, the pores are filled with many metals--iron, nickel, cobalt, zinc, and copper--again by electrolysis. Studies were even performed on the magnetic properties of these deposits (Ref 4). But for reasons to be discussed in a moment, for magnetic recording another step has been interposed: the disk is immersed in 1-percent phosphoric acid, dissolving the inner wall of the pores and increasing the pore diameter, D_p. The disk is then electrolyzed in an iron sulfide bath, filling the pores with iron. The iron grows from the bottom up as a single crystal whose [110] cubic axis is along the pore axis. Finally the disk is coated with an inert protective layer of SiO_2, about 200 Å thick.

The demagnetization field of the needle-shaped element is the dominant force on the iron moment, but it suffers some small competition not only from the magnetic anisotropy field of the iron crystal (the [110] is not the easy axis) but from dipolar interactions with the other needles in the array. Hence the moment lies close to but not exactly along the needle axis. Mossbauer measurements (Ref 3) show an average deviation of 15°. Kawai and Ueda (Ref 5) reported depositing ferromagnetic metals and alloys whose easy axis is along the needle axis.

Demagnetization also breaks up the moment of each needle into numerous (tipped) domains. The coercive force, H_c, is defined as the magnetic field perpendicular to the disk plane required to saturate (to overcome the demagnetization energy with Zeeman energy, so that the moment of the needle is single domain). It was discovered by Kawai and Ueda (Ref 5) in early perpendicular recording studies that the coercive force is too large to be commercially attractive, but it can be reduced by increasing the pore diameter. This is the purpose of the pore widening phosphoric acid bath (Ref 6, 7). Figure 2 shows how H_c drops off with increasing pore diameter. Thus at a pore diameter of 450 Å, the saturation field is about 1,000 Oe. Figure 3 shows the hysteresis curve for a disk with this pore diameter. The coercive force is indeed seen from the figure to be about 1,000 Oe. The curve is nicely rectangular (after correcting for demagnetization, of course). Energy dissipated in going through a cycle, the area within the hysteresis loop, is reasonable.

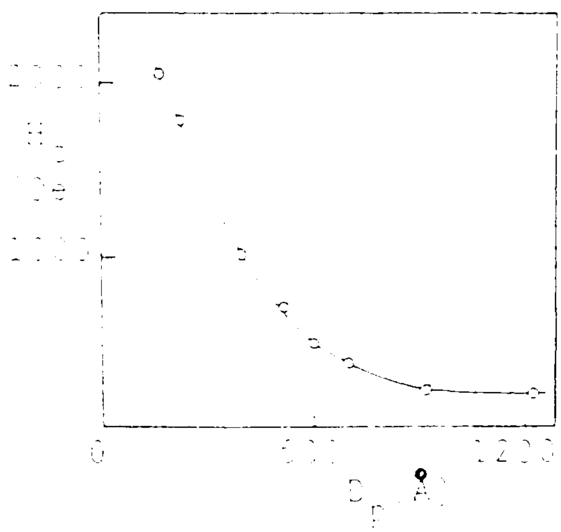

Figure 2. Dependence of the coercive force, H_c, on pore size, D_p. For all films, cell size was 1,400 Å.

Frei, Shtrikman, and Treves (Ref 8) studied the dependence of the coercive force of a long, thin ferromagnet on radius. The situation they analyzed is not exactly the current case--Frei et al. considered the crystal to be oriented with its easy [100] axis along the long axis of the needle--but still gives some insight. They find that

$$H_c = a + b/r^2$$

Here the constants a and b are proportional to the anisotropy energy and exchange energy, respectively. Extrapolations on Figure 2 show this analysis to be at least approximately right, and with not-too-unreasonable constants. For a [110] oriented crystal the situation is a little different, since the surface of constant energy is elliptical, not circular. The problem, an interesting one, has not been addressed theoretically.

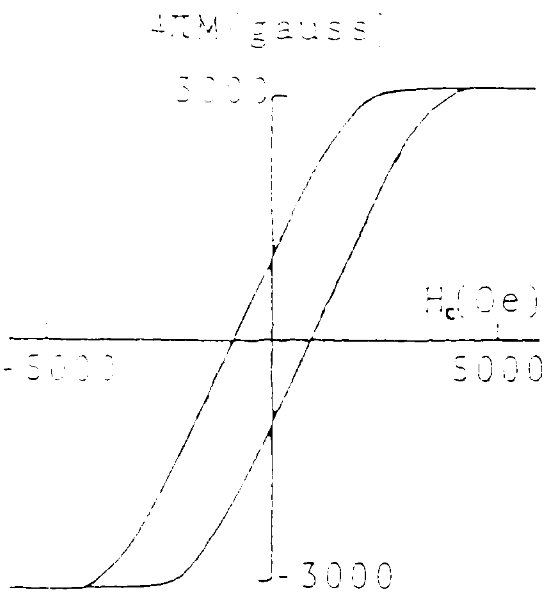

Figure 3. Hysteresis curve. In this film the cell size was 1,180 Å and the pore size was 450 Å.

The saturation magnetization of the film is proportional to the packing factor, $(D_p/D_c)^2$. The pore diameter is determined by monitoring the voltage versus time in a re-anodizing process (Ref 9). The packing factor can then be calculated. Thus it is now possible to measure and control the important parameters of the system and to optimize design.

CONCLUSIONS

In magnetic recording the limitation on information storage and retrieval is now set not by packing density but by the reading and writing process. With a flying height of 0.12 μm, a Mn-Zn ring head with 0.5-μm gap, and a 20-μm track width, typically about 10 kilobits/cm are distinguished. Signal-to-noise is excellent, and the overwrite modulation is less than −30 dB. There is an enormous problem of maintaining uniform flying height, and 0.12 μm seems to be about the lower limit on flying height; a fleck of dust can be catastrophic. But this is a problem not of the anodic oxidized disk approach but of the read/write technology. It would seem that the future lies elsewhere, perhaps in magneto-optics.

The disks prove to be rugged. They have been run for 1,000 hours, with 30,000 start-stop tests, without degradation. After exposure for 72 hours at 40 °C and 75-percent relative humidity to an atmosphere containing 3 ppm H_2S and 10 ppm SO_2, the disks continue to perform without apparent deterioration.

Finally, we emphasize that the anodic oxidation approach is not without competitors. Films of Co-Cr, Co-Cr-Rh, Co-V, Fe-Cr, and Ba-ferrite are under investigation. For making tapes, continuous vacuum deposited Co-Cr films with perpendicular anisotropy are reported to be already competitive with conventional particulate tapes (Ref 10). In time it should be possible to apply the anodic oxidation technique to tapes and cards, as well as to disks. But that is for the future to tell.

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Noboru Tsuya is a Professor of Physics in the College of Engineering of Hosei University, in Tokyo. He was previously a Professor of Physics in the Research Laboratory for Electrical Communications of Tohoku University, in Sendai. Prof. Tsuya is an associate editor of the Japanese Journal of Applied Physics. *He has made major contributions to the development of Sendust and of high permeability silicon–iron.*

Tadeo Tokushima is a research physicist in the laboratories of the Yamaha Company. His interests are in magnetic recording and electronics.

Earl Callen, who joined the Office of Naval Research, Liaison Office Far East in Tokyo in June 1987, serves on a 2-year appointment. He was a Professor of Physics at the American University, in Washington, DC, and is a Professor Emeritus of that institution. Dr. Callen's field of interest has been condensed matter physics, particularly the magnetic properties of solids.

THE MARINE SCIENCE DIVISION OF THE CENTER FOR EARTH SCIENCE STUDIES

Wayne V. Burt

The Marine Science Division of the Center for Earth Science Studies is primarily interested in studying ocean waves, beach erosion, wave refraction, coastal mineral deposits, shelf dynamics and estuarine hydrography, and marine pollution.

INTRODUCTION

The Center for Earth Science Studies in Trivandrum, India, has a regional center in the city of Cochin. The regional center is primarily interested in marine sciences, particularly in ocean waves, erosion of beaches, estuarine dynamics, coastal currents, and upwelling of southwestern India.

The energetic, young Scientist-in-Charge of the center, Dr. M. Baba, is the only Indian scientist I have met so far who received his advanced training in the U.S.S.R., where he received a Ph.D. degree in ocean engineering.

The Center for Earth Science Studies is unique in this part of the world because it is autonomous and not a national governmental entity. It was set up by the state government of Kerala, which provides most of its support.

WAVE CLIMATE

Several locations along the Kerala coast are undergoing severe erosion. The coast is heavily populated, sometimes right down to the beaches. Sea walls have been built for the last 30 or 40 years, but the coastline is pounded so hard by waves during the monsoon season that the sea walls just do not work. In order to combat the problems, various coastal engineering projects are being contemplated. Wave data are needed for design purposes. No basic data were available when the center started its program of making wave observations in 1980.

Wave records were collected at 3-hour intervals for a full year at four locations along the coast, using pressure-type recorders. These data were subjected to spectral analysis to determine the spectral characteristics of the waves at different places and at different seasons of the year. The spectra, in general, have a prominent peak at all times of the year at all locations. The peak frequency ranges from 0.06 to 0.125 hertz (8 to 17 seconds). The shifts of the main peak to higher frequencies are usually observed during the summer months of the southwest monsoon. Secondary peaks at lower frequency indicate the presence of swell. The longer period swells dominate the spectra from September to May. The grouping of swell that has traveled long distances and spectral form and statistical characteristics of shoaling waves have also been studied.

Wave-induced longshore currents have been studied and methods for predicting these currents have been tested and used to determine relationships between waves and longshore sediment transport.

Wave data for a 5-year period have been used to determine the wave power potential along the coast of Kerala. The average wave power varies from 15.5 kW/m (i.e., 1.34 hp/m parallel to the coast) during the summer monsoon months to an average of only 4.5 kW/m during the fair weather period from November to April. The variations in the mean wave power from year to year were negligible.

The center is using numerical models for wave hindcasting from weather maps. It has moored waverider buoys in deep water off Cochin and Trivandrum for 3 years in order to obtain deep water data to be used in evaluating wave hindcasting models.

The center plans to continue gathering wave data for another 3 years so that it will have 10 years of data to use.

WAVE REFRACTION

The Kerala coast has a very wide, very gently sloping shelf. Standard digital computer programs to study wave refraction have not been previously tested on coasts of this type. The center found that these programs worked as well on data from the Kerala coast as they had on steeper coasts elsewhere. The center regularly uses numerical methods to determine where wave energy is concentrated along the coast.

COASTAL MINERAL DEPOSITS

The center has an ongoing program of studying the mineral deposits on the beaches and the continental shelf. Many places are rich in placer deposits.

Fifty beach samples from Kerala showed concentrations of heavy minerals ranging from 22 to 90 percent. The minerals include ilmanite, sillimanite, zircon, monozite, and garnet, the first two of which are being exploited by industry. February samples had maximum concentrations of heavy minerals. Lower concentrations occurred in September and November. In addition, white quartz sand is mined for use in manufacturing ceramic and shell deposits for making white cement. Some phosphorite has been found but has not been exploited.

SHELF DYNAMICS AND ESTUARINE HYDROGRAPHY

Two new programs have recently been initiated. One is to determine the relationships between the circulation on the continental shelf and local meteorological conditions. The second is to determine the effects of coastal upswelling on the circulation and flushing rates in estuaries.

COASTAL OCEANOGRAPHIC DATA ACQUISITION SYSTEM (CODAS)

This system provides long-term simultaneous "in-situ" measurements of a large number of coastal oceanographic and meteorological parameters. The system was developed because of the high cost and excessive use of manpower required to collect these data by other means. Special care was taken to design and construct the system with indigenous materials and technology.

CONSULTING

The oceanographers at the center render consulting services to various state, national, and international agencies. Their projects include harbor developments, coastal zone management, interannual monsoonal studies, national cruise planning, the international Tropical Ocean/Global Atmosphere Program (TOGA), and regional developmental studies of India's offshore islands.

MARINE POLLUTION

The chemists at the center are primarily interested in pollution problems created by industrial development. Most of the industrial development is taking place near estuaries and inland waterways. Large amounts of zinc, mercury, petroleum products, and pesticides are finding their way into the marine environment. They are starting off with testing for the heavy metal content in the water, the sediments, and biota of the estuarine and coastal marine systems.

The address is: Center for Earth Science Studies, Regional Center, Cochin–692018.

Wayne V. Burt received his Ph.D. from Scripps Institute of Oceanography in 1952 (UCLA). Dr. Burt was Science Attache for Oceanography and Meteorology in the American Embassy in New Delhi, India, from October 1986 to April 1987. Previously, he was a professor at Oregon State University and served as a liaison scientist of oceanography and meteorology for the Office of Naval Research, London, from 1979 to 1980. Dr. Burt's current interest is in air–sea interaction.

STATUS OF FRACTURE MECHANICS METHODOLOGY FOR CERAMIC MATERIALS

Edward Mark Lenoe

Over the past 15 years, substantial improvements have been achieved in advanced fine ceramics. Considerable progress has been made, from the materials properties viewpoint, to improve strength, toughness, creep, and environmental resistance. For example, tension and fracture toughness data have been accumulated, thereby addressing deficiencies in the data base. Procedures to induce sharp cracks in fracture toughness specimens have evolved, which should permit accurate and representative characterization of fracture toughness of ceramics. Refinements in analytical approaches are also evident. However, procedures for predicting service life times remain in a fairly primitive state, particularly for environmental extremes. Methods for low temperature designs for components can be relatively reliable, but under severe environments, such as extremely high temperatures, behavior predictions are problematical. In this article, methodologies for fracture analysis are reviewed and some reasons for these predictive problems are provided. The emphasis of this article is on accomplishments in Japan.

INTRODUCTION AND BACKGROUND

This discussion begins with a prologue that briefly describes for nonspecialists the development of structural integrity methodology. These remarks are fueled by a personal sense of frustration because of the general lack of use of available applied mechanics methodology. So it is worthwhile to begin with some historical background to provide a perspective of the status of fracture mechanics methodology for ceramics as contrasted to the general situation for other materials.

From a societal as well as an engineering standpoint, costs of failure of systems are of great concern. A number of years ago Duga et al. (1983) provided an indepth survey of costs of fracture in the United States. The report attempted to answer the following questions:

- What is the total cost of fracture in the U.S. economy? It was estimated that the resources consumed in anticipation of, or as a result of, fracture amounted to $99.0 billion annually (in 1978 dollars).

- How much of these costs could be reduced by applying presently known technology? About $30 billion could be saved if all best known fracture control practices were applied throughout the productive economy.

- How much of these costs could be reduced by further research into fracture-related technologies? It was estimated that future research could reduce these annual costs to the U.S. economy by an additional $23.4 billion.

Considering the impact of fracture and failure, it is understandable there is great impetus for the development of fracture prevention technology. In order to discuss the current situation, it is useful to have a few definitions of terminology.

In general, structural integrity implies that a structure or machine performs well or acceptably according to some set of definitions, such as ability to sustain maximum loads and deflect within required limits or complete desired functions. By application of appropriate engineering technology, the failure rates can, in most instances, be controlled or varied. However, failure rates are a matter of social acceptability as well as numerous other factors. In many instances, the public is exposed to much higher risks than necessary, and much higher than imagined in the common perception.

Reliability mechanics encompasses statistical theories, applied mathematics, continuum and structural mechanics, and engineering methodology generally required to conduct probabilistic design and analysis to estimate failure rates, lifetimes, and subsystems or subcomponent probability of survival with specified confidence limits. Reliability mechanics also encompasses process control, appropriate use of nondestructive evaluation, proof testing, and other avenues to enhance or control system performance. Over the course of more than 50 years, this engineering discipline and probabilistic design and analysis procedures have grown to an impressive repertoire. The scope of possible reliability computations and their accuracy continue to increase largely due to the vitality of computer technology and the continued enhancement of numerical computation power, all at decreasing costs.

Next let us consider the definition of fracture mechanics. At the simplest strength of material level, and to those with limited mechanical engineering or applied mechanics knowledge, fracture mechanics might merely imply the measurement of a "fracture toughness" and subsequent selection and application of a material based simply on the highest measured apparent fracture toughness. Materials selection in this simplistic approach is often, therefore, made with little regard for the more complex aspects of design and analysis, and many fracture mechanics studies of advanced ceramics suffer from lack of an interdisciplinary approach.

Pellini (1976) has presented an excellent review and discussion of the principles of structural integrity technology, covering 25 years of research and development at the Naval Research Laboratory (NRL) under sponsorship of the Office of Naval Research (ONR).

Pellini points out that the systematic development of scientific principles into a mature engineering technology involved direct costs exceeding $100 million. Laboratory research accounted for about one-fourth of the cost and experimental applications and trials accounted for the balance. Unfortunately, many materials scientists and developers are not well versed in structural integrity technology or its utility in development of engineering applications. Far too many elementary models of ceramic fracture phenomena have been proliferated, much to the detriment of systematic scientific development and application of these materials.

PROGRESS IN FRACTURE PREVENTION

Materials and the structures, machines, and industrial products made from them are all subject to failure. The history of efforts to avoid structural failure is long and fascinating, replete with spectacular bridge and building collapses; tank explosions; nuclear powerplant failures; and aircraft, spacecraft, and other disasters. The many structures that have survived over the centuries attest to the success of the early designers and builders. Much of the success was based upon trial-and-error designs and highly redundant use of materials.

It is interesting that most of today's technology in analysis, design, materials, and fabrication has evolved over the past two centuries, although many of the key elements were known or at least observed and frequently practiced long before that. As progress in fracture prevention, one can cite:

- Improvements in design
- Improvements in materials
- Improvements in testing and inspection
- Evolution of safety codes and standards of practice
- Developments in fracture mechanics

IMPROVEMENTS IN DESIGN

Engineering design as we know it today is largely based on the principles of mechanics and the theory of elasticity. Although the foundations of these disciplines can be traced further back into history, the significant developments took place during the 19th century. Further refinements were made during the first half of the 20th century, and these gradually have made their way into industrial design practice during that period. Modern analysis and design methods have evolved during the last 30 years or so following the introduction and rapid use of electronic computing equipment. This technology continues to progress rapidly as further computer-assisted design methods are realized.

Structures are usually designed as follows: materials and geometries are chosen in a first design approximation; estimated loads are determined and verified by test if possible. The behavior is defined in terms of calculated displacements, deformations, stresses, cracking, and estimated rupture conditions. The structure is considered adequate if performance requirements are adequately satisfied over the desired time frame. It is useful to recall that most structures and machinery are evolutionary, and detailed stress analysis is more or less a 20th century phenomenon. In many instances the advent of advanced materials and their introduction precipitated the first detailed three-dimensional stress analysis of many important aerospace components and systems. This is particularly true of advanced composites and ceramics.

It is useful to recall that the adequacy of a design certainly depends on the adequacy of the following: theories used to estimate behavior, the modeling of materials, safety concepts, and failure modes assessments. Design methods based on allowable stresses were the most generally used during the first half of this century. The allowable values were somewhat arbitrarily chosen on the basis of observed mechanical properties such as yield and failure stresses. In the last 70 years the allowable stresses used in the design of mild steel structures have more than doubled. This increase was not based on scientific studies but on an overall judgment of the situation and increased confidence due to improvements in the production of steel and in the design and fabrication technology. In general, in the 19th century and the first half of the present century, a structure was considered well designed if the maximum stresses under assumed loads did not exceed values chosen as allowables. The limitation of stresses to allowable values was taken as an overall guarantee of good behavior, although a control of maximum strain and displacements was performed when necessary.

Theories in use to estimate the behavior of structures—"Theories of Structures"—are based on the usual concepts of structural mechanics and complementary hypotheses about the behavior of materials. It is worth stating that even nowadays for important structural ceramics a full set of constitutive equations and failure theories have not been systematically developed experimentally for even a single ceramic material. Most of the activity in this area is occurring in Japan.

IMPROVEMENTS IN MATERIALS/ STANDARDS

With the exception of manmade polymers, the common materials of industry have been used in one form or another for centuries: wood, stone, metals, glass, and traditional ceramic materials. The industrial revolution of the 1800s marked a period of significantly rapid development both in methods of producing materials and in their applications. However, it was not until the 20th century that some understanding was developed of how the composition and microstructure of materials determined their properties, leading to the degree of control in the production of materials that we have today. During the early 1960s, various forms of advanced composites were pioneered in the U.S. During the early 1970s, advanced ceramics were developed and since then many prototype applications have been developed. One might consider that no uniform way of identifying, representing, or characterizing the various types of nitrides, carbides, oxides, etc. has been adopted on a national, let alone international, scale. Especially in the past 10 years, alternative production routes for ceramics, based on modern plastics and chemical production techniques, have been continually developed. There is an ever expanding array of manufacturing equipment with broadening pressure, temperature, and atmosphere control. This situation, to an extent, has impeded the ceramic data base and standardization developments since the prospect of improved materials dampens interest in extensive experimentation on what may rapidly become passé materials. Nevertheless, impressive progress has been achieved in mechanical properties test methods standardization, particularly in Japan, as discussed later in this article.

IMPROVEMENTS IN TESTING/ INSPECTION

Testing and inspection of materials (as distinguished from products) have developed mainly during this century. Before that there was little testing of materials properties, and inspection rarely went beyond visual examinations. With the introduction of rational design methods, it became necessary to characterize the mechanical properties of materials, and equipment for that purpose was developed in the late 1800s. Testing machines have been continually refined and increasingly automated during the past decade to include sophisticated computer control and data reduction systems. For example, the impact test and other dynamic evaluation methods were increasingly used during World War II and the years immediately following, as the problems of brittle fracture of ordnance components and cargo ships received attention.

Inspection procedures likewise received increasing attention during World War II, with such techniques as radiography and magnetic particle analysis. Inspection techniques for the detection of flaws have continued since that time with the development of acoustic emission, eddy current, and ultrasonic systems, many of which are still being refined. Significant progress has been made in enhanced accuracy for detection and characterization of minute flaws and processing anomalies. Further study is required to investigate the controlling influence of such defects on serviceability of ceramic components. On a laboratory scale, various nondestructive evaluation methods have been developed to provide estimates of fracture energies and associated failure modes. Obviously, such information is the key to fracture mechanics life prediction technology.

EVOLUTION OF SAFETY CODES, PROBABILISTIC DESIGN, AND ANALYSIS

For introducing safety according to statistical concepts, it is necessary to define statistical distributions of loads and structural behavior. Statistical distributions of structural behavior have to be derived from the statistical knowledge of mechanical properties and dimensions. This is only possible by using "Statistical Theories of Structures" instead of the usual deterministic ones.

Borges and Castanheta (1971) have provided an excellent text on structural safety and discussed the early studies of structural safety and evolution of safety codes.

In the last 36 years, numerous international and national associations have appointed special commissions to deal with the problems of safety and to improve design rules. In a state-of-the-art report published by Baker in 1973, two main approaches to the treatment of structural safety in codes were seen to be developing: on the one hand, a simplified approach, and on the other hand, the more probabilistically based proposal of Subcommittee E of the American Concrete Institute (ACI) Committee 348 (Structural Safety) (1972). The ACI proposal was based on the earlier work of Cornell (1969). The former approach is usually referred to as the "semi-probabilistic" approach, whereas the latter approach is the so-called second-moment method of reliability analysis.

In the semi-probabilistic approach, the safety of a structure is "insured" by defining loads and strengths so that they individually have such a remote chance of occurring that the combined probability of occurrence of load exceeding load-carrying capacity is improbable. However, no explicit reliability calculations are undertaken and the levels of risk in different structures are unknown.

Second-moment methods of design or analysis attempt to or estimate the reliability of a structure or component either in terms of a reliability under or an estimate of the probability of occurrence of each limit state during the life of the system. The Construction Industry Research and Information Association (1970) makes the point that it is useful to classify the methods of structural reliability on the basis of complexity, the nature of the approximations made, and the way in which reliability is defined.

Current methods for checking the safety of structures tend to fall within at least three categories, namely Levels I to III. The definitions that follow have been proposed by various subcommittees on first order reliability concepts for design codes.

- Level I: A design method in which appropriate levels of structural reliability are provided, on a structural element (member) basis, by the specification of a number of partial safety factors related to some predefined characteristic values of the basic variables. Characteristic values are given as functions of mean values, coefficients of variations, and probability distribution types. For given characteristic values, the partial safety factors may be deduced from Level II, depending on the degree of safety and the variability of the basic variables. Level I methods can be made identical to Level II methods if the safety factors are continuous functions of the means and variances of the basic variables and of the safety indices. Existing Level I methods replace this continuous function by discrete values of the factors.

- Level II: A design method incorporating safety checks only at a selected point (or points) on the failure boundary (as defined by the appropriate limit state equation), rather than as a continuous process, as at Level III. A Level II method involves the identification of this safety checking point by a suitable algorithm and the idealization of the failure boundary in that region. Reliability levels can be defined by safety indices or equivalent "operational" probabilities in the same sense as for Level III methods.

- Level III: Safety checking based on an "exact" probabilistic analysis for whole structural systems, using a full distributional approach, with reliability levels based on agreed failure probabilities, interpreted in the sense of relative frequency. This is the most complex method of reliability analysis. All design variables are expressed in terms of their full probability distribution functions and probabilities of failure are computed by the evaluation of the appropriate convolution integrals. This is the approach suggested by Freudenthal et al. (1966) and by Borges and Castanheta (1971).

With advances in computational method, considerable progress is being made at increasing the level of complexity of reliability computations. For the average practicing engineer, systems of reliability equations are difficult to formulate and their solution invariably requires multidimensional numerical integration or the use of Monte Carlo techniques. **Nowadays in addition to probability of failure estimates, confidence estimates are also being provided by advanced practitioners.** The increasing emphasis on reliability mechanics is clearly motivated by the consequences of failure. Unfortunately, as stated several times earlier, in many advanced materials application areas, generally only the most simplistic approaches have been applied.

DEVELOPMENTS IN FRACTURE MECHANICS

The study of fracture as a phenomenon dates back to about World War I, with the subsequent theories relating the strength of brittle materials to the presence of microscopic flaws. Here again, the problems encountered during World War II with brittle fracture of steels, as well as such postwar problems as the British Comet jet airplane catastrophy and failures of high-strength steel rocket motor cases, provided impetus to the development of fracture mechanics. During World War II, welded "liberty ships" failed at an alarming rate. More than 3,400 failures were recorded from 1940 to 1955. The statistics are impressive: 19 ships of lengths greater than 350 feet fractured in two or were abandoned at sea, 250 suffered complete or dangerous separation, and 1,200 had potentially dangerous hull fractures. The failures were not wartime casualties, rather they were the result of manufacturing or engineering deficiencies. Subsequently, several Comet airliners disintegrated, numerous aircraft landing gear fractured, and various rocket motors and armored tanks failed. During the Korean war, catastrophic fatigue of several large artillery pieces led to extensive investigations of gun tube life prediction technology, and substantial efforts at substantiating failure and fracture experiments were conducted at various Department of Defense (DOD) laboratories.

Fracture mechanics is the unifying factor in mechanical failure prevention since it contains the major components of engineering for safe operation. It is now widely recognized that the strength of a flawed **material** may be significantly lower than that of a perfect material. This finding is embodied in the material fracture toughness property. **Design** and **overload** protection can proceed based on a knowledge of toughness, so that failure load of the body is not exceeded. Testing insures that the material has sufficient toughness and load-bearing capacity for its function. **Inspection** detects the presence of critical flaws and **maintenance** insures that, once detected, they are eliminated or corrected. Certain industries are now using fracture mechanics as a design method--aerospace and nuclear vessels, for example--and current research is active in this field to extend its applicability to more material classes and systems.

Recently Yokobori (1986) provided valuable insight into the current approaches for fracture behavior prediction of brittle ceramics as compared to metals. He correctly points out that much of the current fine ceramics research has been rather superficial. In particular he cites the dichotomy that apparently exists between those developing new materials and those attempting to describe and predict their behavior. Many so-called laws that have been proposed in the field of ceramic fracture are not deductive but rather simplified equations that provide a crude explanation of the predominant phenomena while ignoring other controlling phenomena. The inductive method of gathering data and comprehending the phenomena has not been applied enough. In general, the data base remains fairly limited for high-performance ceramics, and statistical or probabilistic methods are not usually adequately applied either to interpret or verify some highly conjectural physical models.

For instance, most researchers are indifferent to the fact that for linear elastic fracture mechanics (LEFM), the Griffith energy balance equation is necessary but may not be sufficient to fully describe fracture, particularly in severe environments. In that instance a variety of additional considerations must be included in the fracture criteria. Yokobori pleads for an interdisciplinary macroscopic viewpoint that is combined with pertinent microscopic considerations to develop realistic theoretical approaches. Now let us briefly consider several important topics.

Fracture Toughness and Strength

Usami and colleagues (1986) systematically reviewed the literature to determine the effects of flaw size on brittle fracture and static fatigue. As they point out, although small flaws are frequently observed at fracture origins and are considered to be a major cause for strength scattering, the relationship between crack size and strength is not sufficiently clear. In many ceramics cracks may grow under sustained static load at elevated temperatures or in certain environments, but in this circumstance, too, small crack behavior is not thoroughly understood. Therefore, they provided this review of the effects of flaws and grain sizes on brittle fracture strength as well as static-fatigue behavior in ceramics.

Flaw Size Effects. Based on fairly extensive data they reported that room temperature fracture stress in amorphous glass of very small structural size maintains a simple linear elastic fracture mechanics (LEFM) relationship, even for small flaws. On the other hand, for polycrystalline ceramics, although large flaws follow the LEFM relationship, small flaws deviate from the relationship for small-flaw controlled strengths. Many flaws that govern component strength fall outside the range of applicability of LEFM, even at room temperature conditions, and may give unsafe strength predictions. In general, the strength relationships for all the materials were almost identical for surface scratches, large crystals, pores, controlled surface flaws (CSF) introduced by Vicker's or Knoop indenting, as well as for acute notches. They report that fracture toughness was highest for sialon and silicon nitride, followed in sequence by silicon carbide, alumina, and glass.

Regarding the effects of small flaws in polycrystalline ceramics, the test results for different materials and grain sizes all fall in a relatively narrow scatter band, which suggests a simple grain fracture model based on an original crack tip equivalent to twice the mean grain diameter of a large weak grain. Their results of relationships between equivalent crack length and fracture stress for various materials and fracture toughness methods are summarized in Figure 1. Results from other researchers are also superimposed in the graph (Richerson and Johansen, 1981).

Usami also applied relationships from the simple grain fracture model (Figure 2) as follows:

For cracked specimens,

$$\frac{K_C}{K_{IC}} = \frac{(1 + r_0/2\,a_c)^{1/2}}{1 + r/a_e}$$

For plane specimens:

$$\sigma_{0,c} = \frac{0.943\,K_{IC}}{(2\,\pi\,r_0)^{1/2}}$$

At room temperature the experimental fast fracture monotonically loaded strength results surveyed fit the model well as shown in Figures 2 and 3 for the dense materials. Richerson et al. (1981) were not able to derive a model for the more porous reaction-bonded silicon nitride (RBSN) that could predict the effects of surface and internal pores and inclusions. Results obtained for strength reductions were all very similar for the various defects in RBSN.

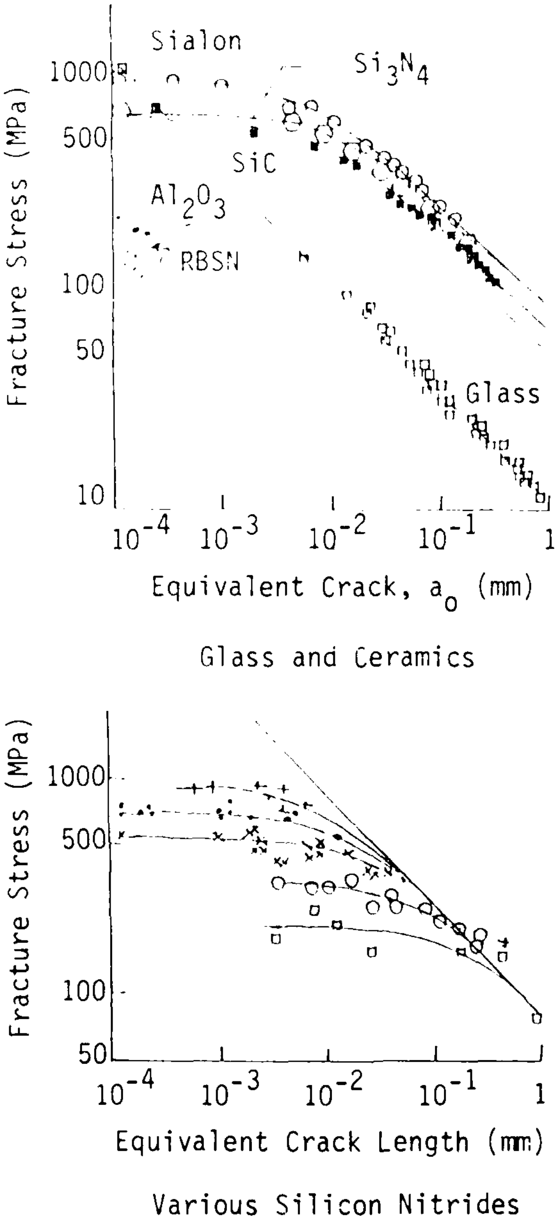

Figure 1. Equivalent crack length versus fracture stress (after Usami et al., 1986 and Richerson and Johansen, 1981).

Environmental Effects on Room Temperature Strength. The term "crack healing" refers to observed environmental exposure effects on room temperature strength of some ceramics. Typically in such experiments, bending strength was measured on as-received and exposed specimens containing controlled surface flaws (CSF). After heat treatment of elevated temperature in air, under no loads, artificial surface flaws were almost eliminated due to evaporation and migration of the material or due to formation of oxides or other effects in and around the cracks. Excessive oxidation at higher temperatures, however, caused pits and surface films to form and resulted in strength reductions for the plain, initially unflawed specimens after exposure.

Usami et al. (1986) presented results for silicon nitride and silicon carbide. Heat treatment increased strength in both these materials with CSF about 20 percent at 800 °C. Exposure also increased CSF strengths at 1,200 °C for silicon nitride and 1,400 °C for silicon carbide. Both air and vacuum environments were used in these heat treatment studies. Similar strength improvements were observed for the silicon nitride in vacuum as in air. For the silicon carbide there was a larger improvement in air than in vacuum. It was speculated that this was caused by an abundance of silicon oxide in the grain boundaries of the silicon nitride.

The differences of internal and surface changes of microstructure are important to the designer. For example, the nature of crack growth and the spatial distribution of microstructural changes will control component failure. **The literature dominated by materials scientists does not appear to be cognizant of the importance of developing usable analytical models to aid the designer in estimating surface layer and internal physical, chemical, and microstructural changes in a realistic and reproducible one-, two-, and three-dimensional manner. The importance of relating such changes to those occurring in actual service components also appears to be ignored.**

Regarding the relationship between the initial equivalent crack length and static fatigue limit at 1,000 °C, unique relationships were observed for different flaws, e.g., for surface scratched, single edge notched beam (SENB), and controlled surface flaw (CSF).

Static and Dynamic Fracture

A number of investigators have studied dynamic and static crack velocity versus stress intensity factor relationships (Usami et al., 1986; Kobayashi and Yang, 1986). Static-fatigue crack velocities did not appear to have any unique or clear relationship with stress intensity factor even for very large cracks in certain ceramics. Smaller cracks show a higher velocity than large cracks at the supposed same stress intensity factor (Usami et al., 1986). Kobayashi and Yang (1986) investigated rate effects and crack arrest phenomena for a variety of materials, specimen configurations, and velocity ranges. They concluded that in some materials there are no unique crack arrest stress intensity factors. In their studies polycarbonate, 4340 steel, reaction-bonded silicon nitride, alumina, and "Homelite-100" were used. The photoelastic polymers were used to attempt to determine dynamic stress intensity factors. Some researchers have shown that "terminal" crack velocity is test specimen dependent. Other authors argue for a unique vertical "stem" or for a non-unique relationship (Daly, 1979; Kobayashi and Mall, 1978; Ravi-Chandar and Knauss, 1983; Kalthoff et al., 1978; and Kobayashi and Mall, 1979). Some of Kobayashi's results are presented in Figures 4 and 5.

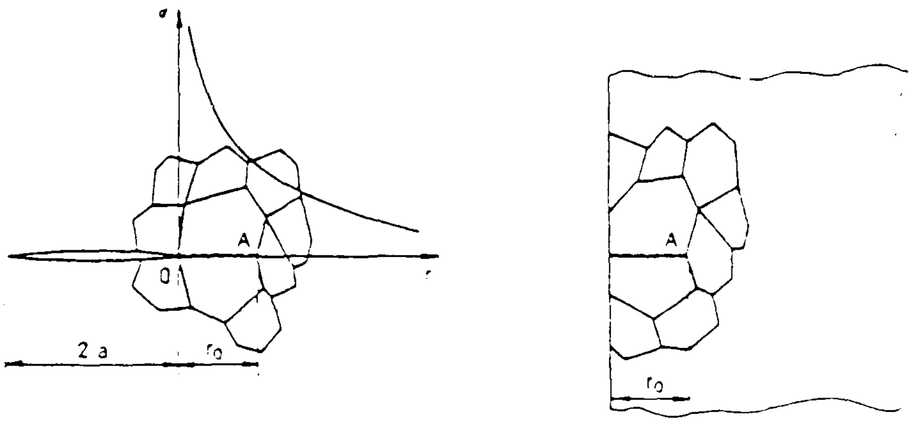

Figure 2. Simple grain fracture model - polycrystalline ceramic.

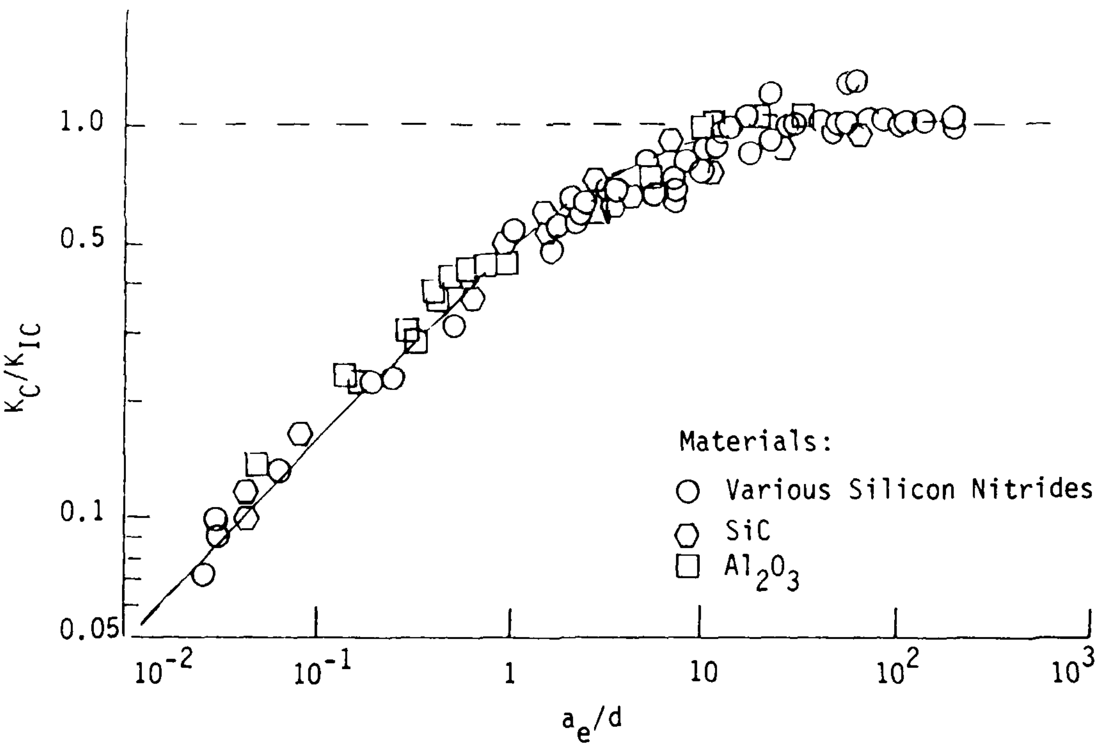

Figure 3. Ratio of equivalent crack length/mean grain diameter versus ratio of critical stress intensity factor values for short and long cracks (after Usami et al., 1986).

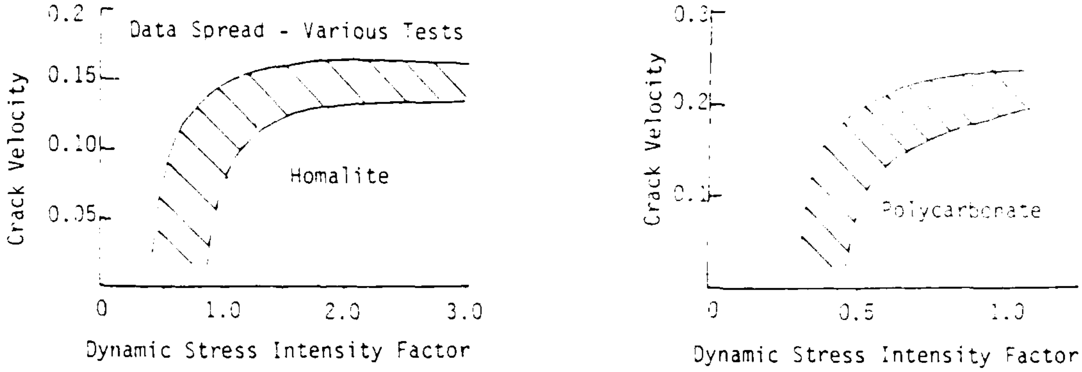

Figure 4. Dynamic stress intensity factor versus crack velocity (after Kobayashi and Yang, 1986).

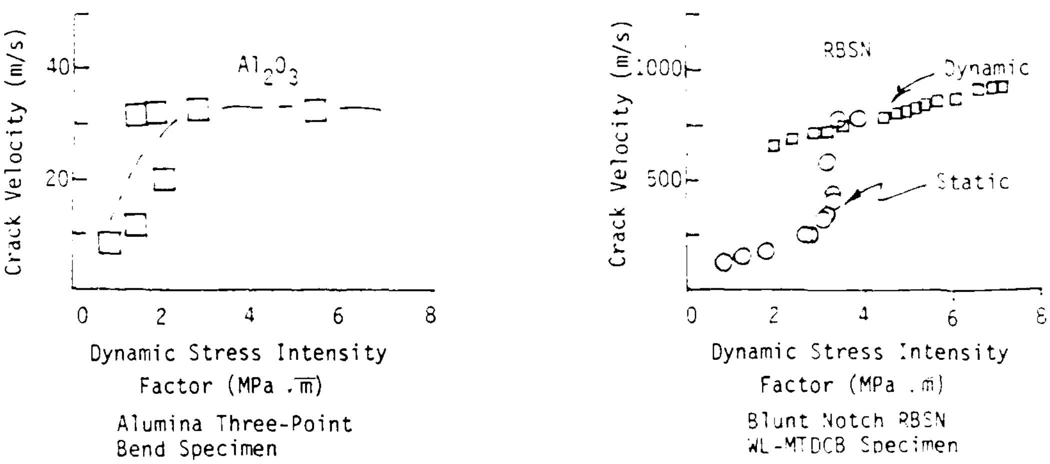

Figure 5. Dynamic stress intensity factor versus crack velocity (after Kobayashi and Yang, 1986).

Fatigue Behavior

Until recently, fatigue of advanced ceramics has not been studied much except in flexural loading modes, which are relatively easily accomplished. Since the engineering property data on oxides, nitrides, and carbides are rapidly increasing, numerous organizations are monitoring the results. Here in Japan, in a 5-year perioc' (1979–1983), almost 200 papers were published on relevant topics. Nonetheless, relatively little tensile fatigue and creep data were available in that period. But that situation has improved markedly in the past 3 years as government, university, and industrial laboratories have accelerated their activities. An updated survey will be useful.

For instance, Fujita et al. (1986) studied the long-term durability of pressureless sintered silicon carbide and silicon nitride. Four patterns of stress and temperature were investigated, including static fatigue, low cycle fatigue, static fatigue and cyclic temperature change, and syncnronized change of temperature and stress. It was found that under static fatigue conditions at temperatures lower than

1,200 °C, no fatigue was observed in alumina containing sintered SiC. At temperatures above 1,300 °C, fatigue due to slow crack growth (SCG) was observed. Sintered silicon nitride showed SCG over about 1,000 °C and had some fracture patterns corresponding to different stages of static fatigue. In all fatigue tests under cyclic stress change, cyclic temperature change, and synchronized cyclic temperature and stress, fatigue characteristics seemed controlled only by accumulation of SCG and no definite acceleration due to cyclic effects was observed for the reported test conditions. Interesting results have also been reported by Tajima et al. (1986).

Conventional ideas state that fatigue failure depends on the degree of tensile stress and not on compressive stress. Actual fatigue in many ceramic materials includes a crack initiation phase from various kinds of initial flaws and a growth stage. Kawakubo and Amano (1987) concluded that compressive stress may affect fatigue life, especially in the initiation phase. They present data that indicate compressive stress accelerates fatigue in sintered silicon nitride.

Contact Stress Effects

Contact stress effects have proven to be a significant design consideration in ceramics. In several early development programs for ceramic engine components, during rig testing, component chipping or cracking at ceramic/ceramic and ceramic/metal interfaces was observed. Starting about 1978, the earliest studies of nitride ceramics were simple compatibility tests of reaction-bonded silicon nitride in contact with various metals and high-temperature lubricants for a range of applied normal loads at different temperatures (Richerson et al., 1981). Based on such evaluations, promising material combinations were selected and coefficients of friction were determined.

Later Richerson and Johansen (1981) summarized their studies to evaluate contact geometry, static-contact versus relative motion, time at temperature, and other variables that might affect surface and interface integrity under contact conditions. Richerson et al. (1981) described the contact test apparatus used. This consisted of a furnace and deadweight load train for imposing a normal load and a separate load train for imposing relative motion while recording the resulting tangential force. They found the variables affecting contact to be:

- Materials
- Temperature
- Time at temperature
- Pre-oxidation
- Load
- Point contact
- Line contact
- Area contact
- Rate of relative movement
- Cycles
- Surface finish
- Chemical compatibility
- Compliant layers
- Lubricants
- Superimposed bend load
- Vibration

The evaluation approaches used were measurement of coefficient of friction, visual inspection, strength, and fractography. Table 1 shows results for various materials. In general, higher density materials had lower coefficient of friction in the unlubricated condition, about the same in the lubricated condition, and greater retained strength.

Table 1. Comparison of Contact Test Results for Alternative Materials and RBSN[a]

Material	Lubricant	Density (g/cm^3)	Baseline Strength (ksi)	Static Coefficient of Friction	Retained Strength (ksi)	Typical Surface Finish (μin rms)
NC-350 RBSN	None	2.50	47.8	0.80	19.0	
	CoO + DTE-25			0.20	28.0	
RBN-101 RBSN	None	2.72	33.5	0.70	18.0	10
RBN-104 RBSN	None	2.78	45.1	0.42	27.7	
	CoO + DTE-25			0.36	38.7	
Sintered αSiC	None	3.12	45.8	0.45	32.1	6
	CoO + DTE-25			0.20	48.1	
NCX-34 HPSN	None	3.35	121.0	0.61	89.9	7
	CoO + DTE-25			0.27	143.9	
REFEL Si-SiC	None	3.09	55.4	0.62	80.1	4
	CoO + DTE-25			0.40	53.2	

[a]Test Conditions: 57.3-lb normal load; point contact; 2,000 °F 1/2-h hold; 0.060-in relative movement.

Figures 6 and 7 present results for retained strength and coefficient of friction of RBSN under different conditions. Initial test results presented in Figure 6 for bare RBSN with and without relative motion demonstrate that when relative motion was added to the contact load, visible surface damage occurred and the average bend strength was reduced to 20 ksi. Reductions in strength occurred for applied normal loads of 24.7 and 57.3 pounds for the so-called point load condition, that is, for contacting specimens of 0.25-inch radius, crown on crown. Measured contact width for the "point condition" was typically 500 to 700 microns (0.020 to 0.028 inch). Coefficients of friction typically were 0.8 or higher. Hertzian stress analysis and parametric study for line and point contact showed that surface damage could be theoretically predicted for loads above 25 pounds. In an effort to further understand the controlling mechanisms of contact damage, alternative materials with better surface finish, lower porosity, and higher strength were tested. Results are shown in Figure 7.

The general level of activity has increased in recent years in the area of contact stress and tribological behavior of ceramics. The increased activity is particularly impressive in Japan. Several government research centers and numerous industrial laboratories are heavily involved in the evaluation of ceramic coatings and the use of ceramics as bearings and for different types of wear-resistant industrial products. Substantial amounts of data have been accumulated, and this information should be thoroughly assessed in order to improve our design approaches for these applications.

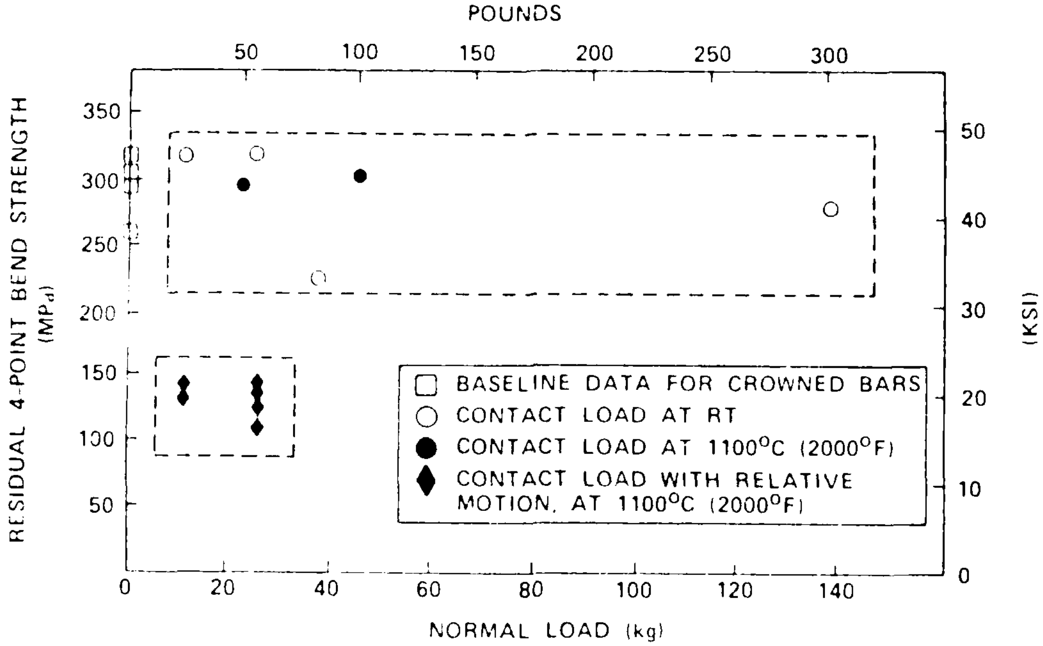

Figure 6. Effect on strength of normal contact load (with and without simultaneous relative motion) (from Richerson and Johansen, 1981).

By way of example, Koyo Seiko Co., Ltd., in joint development with Toshiba, has a total of 68 patents pending for fine ceramic bearings, and other major bearing manufacturers and ceramics producers are also extremely active. Takebayashi and Ueda (1986) reported on rolling contact fatigue behavior of ceramics (see Figure 8). It is clear that silicon nitride bearings have rolling contact lives that exceed that of high-carbon chrome steel. It was found that the rolling contact fatigue life of silicon nitride is about twice that of high-carbon chrome bearing steel in B_{10} life and about four times in median life, B_{50}. Interestingly, the failure behavior does not follow a simple Weibull distribution but is multimodal in nature as shown by Figure 8. Ishikawajima Harima Heavy Industry, in cooperation with several bearings suppliers, also has an aggressive test and evaluation program underway using bearings in transmissions and engines. Quite a number of years ago, researchers in the U.S. conducted various evaluations of ceramic rolling bearing elements, and outstanding fatigue life was proven for hot-pressed silicon nitride bearings. In spite of the earlier entry into bearings applications by the U.S., the practical application of ceramic bearings and spindles appears to be occurring now in Japan.

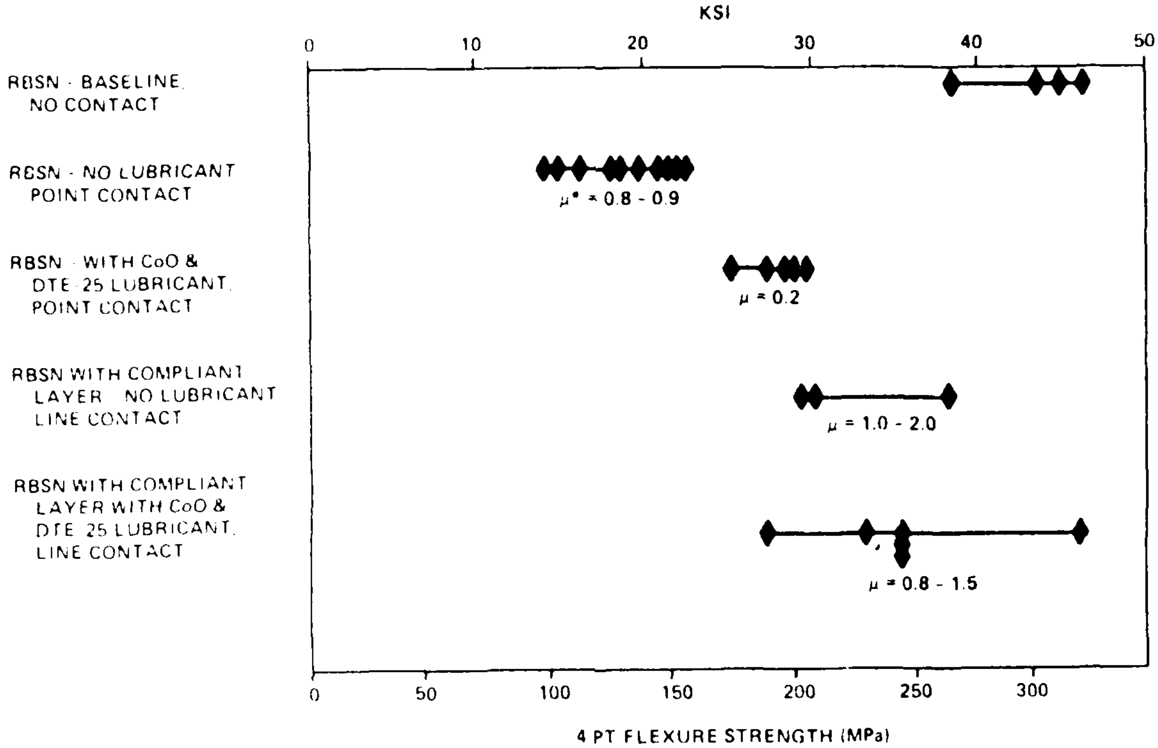

Figure 7. Summary of strength and coefficient of friction results (from Richerson and Johansen, 1981).

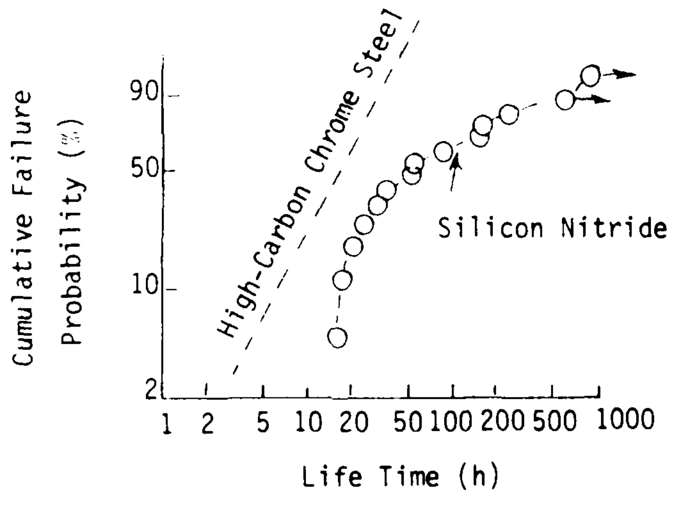

Figure 8. Comparison of steel and silicon nitride bearings (after Takebayashi and Ueda, 1986).

PRESENT SITUATION OF STANDARDIZATION OF TESTING METHODS FOR STRUCTURAL CERAMICS IN JAPAN

TESTING ACTIVITIES

Recently Okuda (1987) described test standardization activities in Japan, and it is gratifying to learn of the level of activities and accomplishments in this vitally important area. Based on extensive surveys within the Japanese engineering community, 12 standardization areas were deemed of importance:

1. Flexural strength
2. Tensile strength
3. Fracture toughness
4. Hardness
5. Modulus of elasticity
6. Oxidation resistance
7. Thermal shock resistance
8. Creep
9. Specific heat
10. Thermal conductivity
11. Coefficient of thermal expansion
12. Abrasion resistance

In considering these various standardization areas, flexural and tensile strength were selected as the first items to be standardized, and indeed the list above is more or less in order of priority. Round-robin evaluations have been underway for some time now in flexure testing, tension, and fracture, and several Japan Standards have been issued or are in preparation. Regarding fracture toughness, various methods have been compared, as discussed later.

Returning to flexural strength, materials tested consisted of pressureless sintered alumina (Al_2O_3), hot pressed silicon nitride, and pressureless sintered silicon carbide (SiC). Tests were conducted ranging from room temperature up to 1,200 °C and 1,350 °C. Silicon nitride and silicon carbide were tested in air, in vacuum, and in nitrogen atmospheres. Three companies (designated A, B, and C) performed the flexure tests using about 30 specimens per condition. Note: Weibull modulus was calculated by the method of least squares.

Results for flexural strength are shown in Tables 2, 3, and 4. As regards average strength, standard deviation, and Weibull modulus, very good agreement was observed for the 1,200-°C tests on alumina and silicon nitride and also for the 1,350-°C tests in air on silicon carbide. However, the results on silicon nitride at 1,350 °C show large variations. It was assumed these differences could be attributed to a plastic deformation that occurs at this temperature and also due to the fact that the atmospheres in which the tests were conducted probably differed as well.

Room temperature tensile testing was also reported by Okuda (1987). In this case about 20 replicates were completed for each test condition. Three companies used their own test procedures for the experiments on pressureless sintered silicon nitride, and a similar specimen surface roughness of about 3 microns maximum was used. Cross head speeds were 0.1 to 0.5 mm/min. Strain gauges were used to document bending strains. Results are shown in Table 5. Note the substantial differences reported in Weibull modulus and tensile strengths. When experimental conditions are compared, differences in surface roughness, specimen holding methods, and bending strains are evident. Notable differences also occur in initial fracture locations, for instance, surface versus interior failure. Generally, specimen failures for company H tests were interior. It is not clear whether this is due to surface roughness or holding methods. After these early results in the 1984-1985 period, additional testing was conducted and the tests were extended to include alumina and silicon carbide as well.

Table 2. Experimental Results on Measurement of Flexural Strength at 1,200 °C (Alumina and Silicon Nitride)

Item	Results for Experimenter--		
	A	B	C
Experimental Conditions			
Type of bending test	3-point	3-point	3-point
Heating time to 1,200 °C, min	6	5	5
Holding time to 1,200 °C, min	5	5	5
Atmosphere in heating	air	air	air
Material for supporting tools	fused Al_2O_3	sintered Al_2O_3	sintered Si_3N_4
Experimental Results			
Alumina			
Mean value of strength, kgf/mm^2	22.1	22.5	22.18
Standard deviation, kgf/mm^2	2.9	3.1	3.58
Weibull modulus	8.8	8.6	6.3
Silicon nitride			
Mean value of strength, kgf/mm^2	45.8	44.7	44.72
Standard deviation, kgf/mm^2	3.5	3.3	3.39
Weibull modulus	15.9	16.5	14.0

Table 3. Experimental Results on Measurement of Flexural Strength at 1,350 °C (Silicon Carbide)

Item	Results for Experimenter--		
	D	E	F
Experimental Conditions			
Type of bending test	3-point	3-point	4-point
Heating time to 1,200 °C, min	7	5	50 °C/min
Holding time to 1,200 °C, min	5	5	10
Atmosphere in heating	air	vacuum	air
Material for supporting tools	sintered Si_3N_4	graphite, SiC	sintered SiC
Experimental Results			
Alumina			
Mean value of strength, kgf/mm^2	44.6	40.2	41.4
Standard deviation, kgf/mm^2	7.4	6.9	6.7
Weibull modulus	7.0	6.8	7.4

Table 4. Experimental Results on Measurement of Flexural Strength at 1,350 °C (Silicon Nitride)

Item	Results for Experimenter--		
	D	E	F
Experimental Conditions			
Type of bending test	3-point	3-point	4-point
Heating time to 1,200 °C, min	7	27	50 °C/min
Holding time to 1,200 °C, min	5	5	10
Atmosphere in heating	air	air	N_2, 0.7 MPa
Material for supporting tools	sintered Si_3N_4	sintered SiC	sintered SiC
Experimental Results			
Alumina			
Mean value of strength, kgf/mm^2	16.7	12.3	42.5
Standard deviation, kgf/mm^2	1.2	1.2	5.9
Weibull modulus	16.7	12.2	8.0

Table 5. Results of Tensile Test for Pressureless Sintered Silicon Nitride

Item	Results for Experimenter--		
	G	H	I
Mean strength, MPa	420	537	483
Standard deviation, MPa	57	36	63
Weibull modulus	8.6	17.8	8.9
Ratio of bending stress to tensile strain, %	4.9	3.8	2.4
Fracture origin			
Surface	0	16	5
Interior	20	6	15
Holding method of test piece	collect chuck	powder cushion	collect chuck and bearing
Surface roughness, R_{max}, μm	<3	1.8 (mean value)	<2
Gauge length, mm	3ϕ X 24	6ϕ X 24	6ϕ X 24
Total length of test piece, mm	64	120	170
Diameter of chuck parts, mm	8ϕ	16ϕ	18ϕ

As far as fracture toughness testing, the following methods have been investigated:

1. Chevron notched method (CN method)

2. Single-edge notched beam method (SENB method)

3. Controlled surface flaw method (CSF method)

4. Indentation method (sometimes called indentation fracture method or indentation microfracture method)

The various notch and indentation flaw geometries used are shown in Figure 9 and results obtained are presented in Tables 6, 7, and 8. The K_{IC} values reported in Table 6 for the chevron notched method are quite different, perhaps due to varying notch shape. The single-edge notched beam method gave the highest apparent K_{IC}. This method is sensitive to notch width, which in this case was set at 0.2 mm. As for the indentation method, K_{IC} values obtained by each company (Table 8) are in comparatively good agreement. However, when calculating K_{IC}, a number of problems are evident, including measurement of crack size and appropriateness of calculation method. Note that data presented in Tables 6 through 8 were obtained in 1984. Since that time additional materials and test conditions have been evaluated. There are numerous data bases that have been generated in Japan by industry, government, and university laboratories. These remain to be systematically assessed and reported.

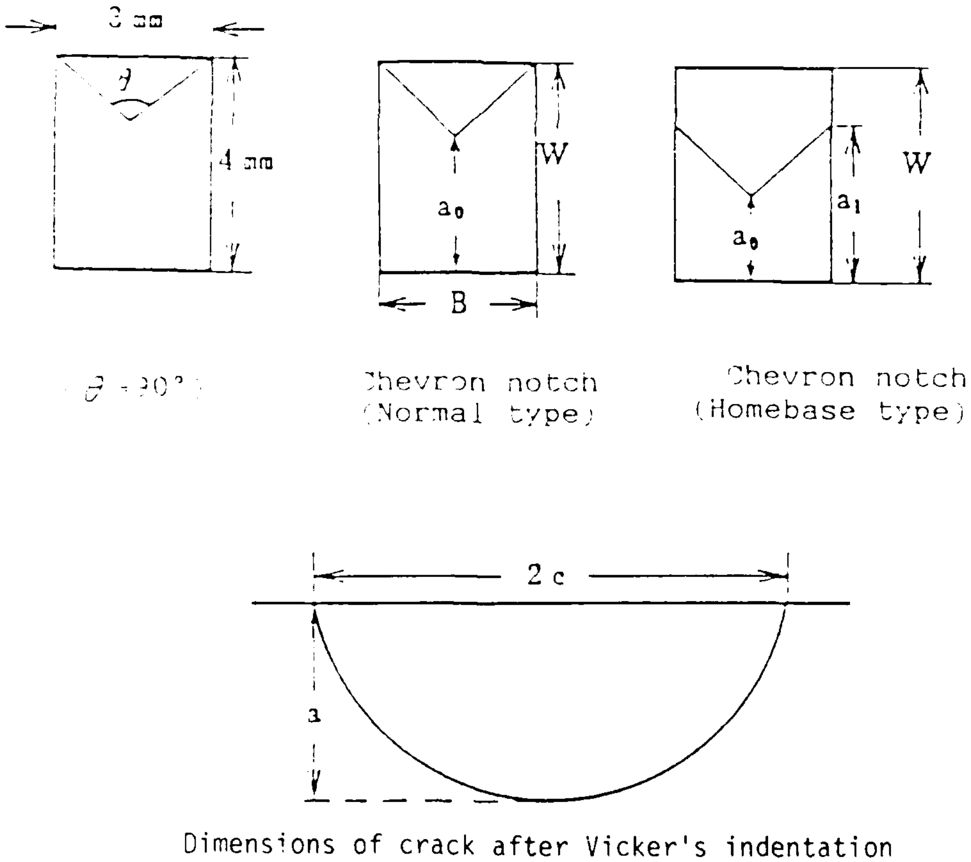

Figure 9. Notch and indentation flaw geometries.

Table 6. K_{IC} of Pressureless Sintered Si_3N_4 by Chevron Notch Method

Type of Bending Test	Cross Head Speed (mm/min)	K_{IC}[a] ($MN/m^{3/2}$) for--		
		J Co.	K Co.	L Co.
3-point	0.5	2.91	3.88	4.88
3-point	0.005	3.08	3.51	4.51
4-point	0.5	3.40	3.79	4.04
4-point	0.005	3.77	3.72	3.88

[a]Mean value of five measurements.

Table 7. K_{IC} of Pressureless Sintered Si_3N_4 by Single-Edge Notched Beam Method

Type of Bending Test	Cross Head Speed (mm/min)	K_{IC}[a] ($MN/m^{3/2}$) for--		
		J Co.	K Co.	L Co.
3-point	0.5	7.32	6.03	7.16
3-point	0.005	5.85	5.44	6.18
4-point	0.5	6.96	6.41	6.37
4-point	0.005	6.42	5.73	5.62

[a]Mean value of five measurements.

REQUIREMENTS FOR IMPROVED TESTING

Precracking Method

In the early development of fracture mechanics approaches for metals, the importance of using a "natural" crack was not recognized. Of course, it is difficult to introduce such cracks in brittle materials. Therefore, it is of fundamental interest to learn of the approach by Nippon Steel researchers. Nose and Fujii (1986) have reported a successful technique for precracking ceramics. The method uses a specially devised anvil to load a Vicker's indented beam specimen and is characterized by a pop-in cracking procedure that leads to a straight through precrack. Apparently the method gives substantially the same fracture toughness over a wide range of precrack lengths and is applicable at elevated temperatures. Figure 10 illustrates the method, and Figure 11 shows some results on alumina (Al_2O_3). The boxed-in single-edge precracked beam (SEPB) data show significantly less scatter than either the indentation method or the single-edge notched beam (SENB). Table 9 presents results obtained by Nose and Fujii (1986).

While substantial efforts have been completed towards the standardization of test methods, more powerful testing and investigation methods are required. Much exchange of information remains to be accomplished and further cooperative efforts will prove fruitful in avoiding excessive duplication of efforts.

Uniform Test Fixtures and Procedures

One of the major obstacles to use of ceramic materials has been the lack of acceptable design data. As compared to other materials, design data for ceramics are of relatively poor quality. Part of this problem can be attributed to the lack of standardization of test methods for high-performance ceramics. In the United States the ceramics community currently uses a myriad of sample sizes, fixture types, and testing procedures. Thus, there are serious problems of data compatibility and reproducibility, and numerous reported data contain serious experimental errors. The situation regarding proliferation of specimen sizes and fixtures has not improved significantly since Quinn, Baratta, and Conway (1982) conducted a survey to determine types of fixtures and specimen configurations being used for strength testing of high-performance ceramics. While the survey was not intended to be exhaustive, a wide variety of fixtures was identified. About 137 fixtures were found to be used, and only a few establishments in the United States were using even metric dimensions. Figure 12 is a histogram of the outer spans being used in three- and four-point flexure fixtures. A fairly large number of U.S. organizations had samples with 1/8- by 1/4-inch cross sections. Unfortunately, there was no consistency with respect to specimen lengths or fixture spans. The U.S. Army Materials Technology Laboratory, based on surveys and supporting experimental studies, proposed a military standard (MIL-STD-1942(MR), "Flexural Strength of High-Performance Ceramics at Ambient Temperature"). Currently, however, there are no consentient standards for high-performance ceramics.

Table 8. K_{IC} of Pressureless Sintered Si_3N_4 by Controlled Surface Flaw Method

Type of Bending Test	Cross Head Speed (mm/min)	Method of Removal of Residual Stress	$K_{IC}{}^a$ ($MN/m^{3/2}$) for--		
			J Co.	K Co.	L Co.
3-point	0.5	Trial 1	4.85 (5.20)[b]	4.43	4.38
4-point	0.5	Trial 1	4.49 (4.72)[b]	4.32	4.26
3-point	0.5	Trial 2	4.44 (4.52)[b]	3.80	3.74
4-point	0.5	Trial 2	4.28 (4.35)[b]	3.88	3.63

[a]Mean value of five measurements.
[b]M value used in the calculation formula was calculated from the measured values of a, c, and b.

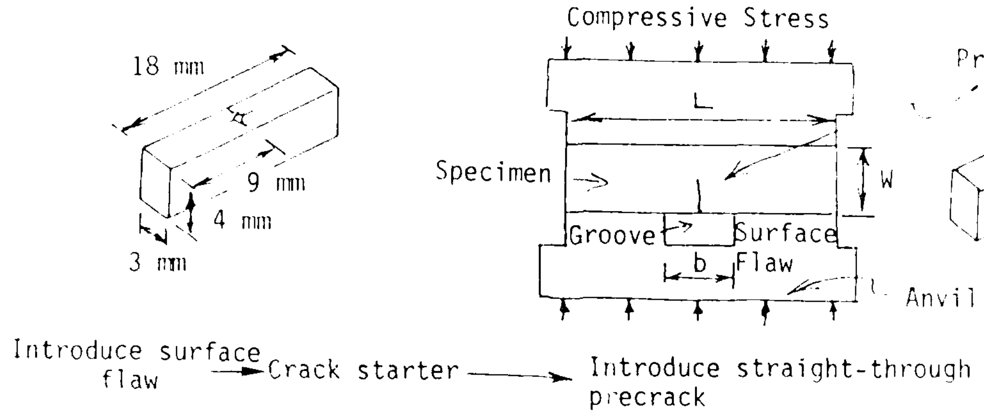

Figure 10. Schematic of precrack method.

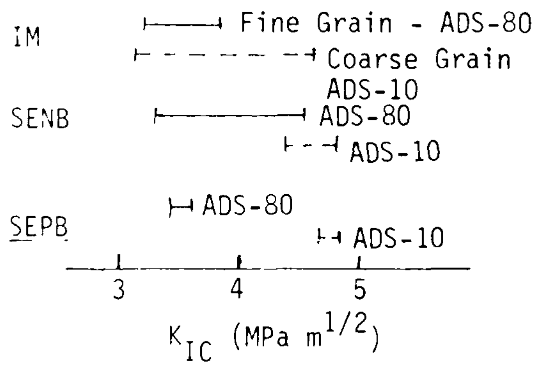

Figure 11. Comparison of results (Al_2O_3). Scattering of data by SEPB method is very small compared with others.

Improved Analysis of Fracture Specimens

McKinney and Wu (1983), of the Naval Research Laboratory, describe data acquisition methodologies for failure prediction in ceramics. They point out that the studies of crack velocity versus stress intensity factor reported by Weiderhorn (1969) used equations for stress intensity factor for the compact tension specimen based on the work of Srawley and Gross (1967). In this specimen configuration, at constant load, the stress intensity factor increases with crack length and there is some difficulty in determining crack growth rates at a particular stress intensity. Next they describe the development of the so-called double torsion specimen to try to achieve a crack-length-independent fracture specimen. A source of controversy regarding this type of specimen is that the crack front shape is actually dependent on the material being tested. Several researchers have calculated the changes in stress intensity as influenced by the crack front shape. However, the analysis of various fracture specimens remains a fruitful area of study. Data evaluation procedures could be significantly enhanced by improved analysis of each method and adaptation of uniform data interpretation approaches.

Table 9. Test Results

Materials	Precrack Length, a/w	K_{IC} (MPa $m^{1/2}$)	Scatter of K_{IC} [a]
Room Temperature (in Air)			
T.Z.P. - Nilsen TS	0.440-0.498	9.50	+0.30 (+3.2%) -0.30 (-3.2%)
Al_2O_3 ADS-10 Coarse Grain	0.485-0.542	4.80	+0.08 (+1.7%) -0.09 (-1.9%)
ADS-80 Fine Grain	0.353-0.514	3.49	+0.18 (+5.2%) -0.15 (-4.3%)
SiC - Ibiceram SC-850	0.371-0.674	2.53	+0.14 (+5.4%) -0.13 (-5.1%)
1,773 K (in Air)			
SiC - Ibiceram SC-850	0.526-0.562	3.59	+0.17 (+4.9%) -0.17 (-4.9%)

[a] Scattering of K_{IC} is small (within ±5%) although the crack length varies considerably. There is no problem in the test at elevated temperatures.

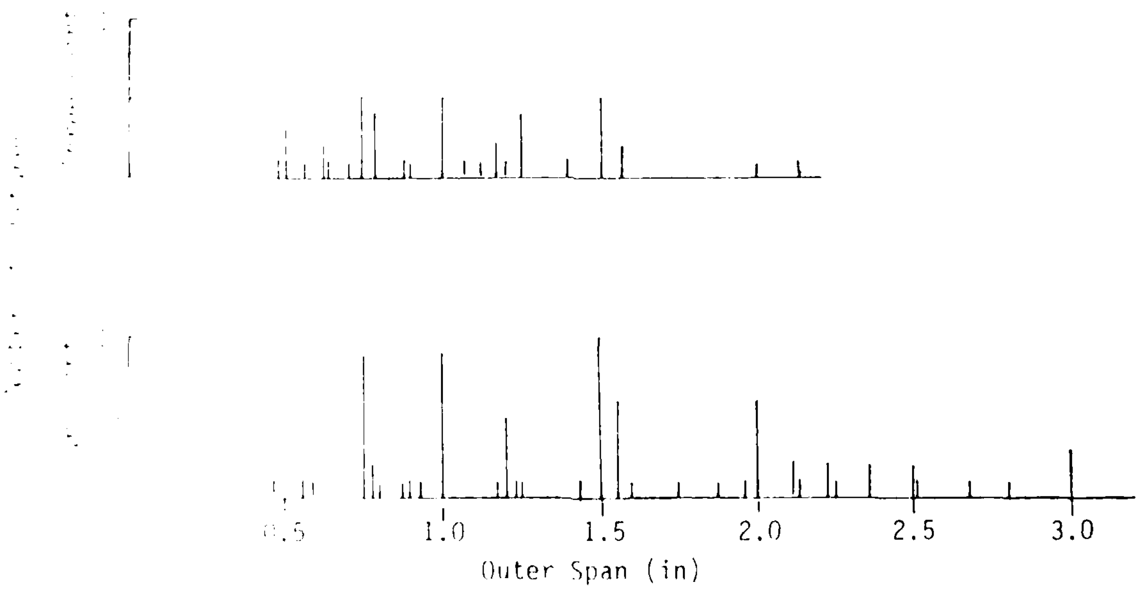

Figure 12. Histogram of outer spans used in three- and four-point flexure fixtures.

Many of the conclusions reached by researchers dealing with advanced ceramics are based on too few data replicates and very little has been done to adequately apply statistical data evaluation techniques in either the western world or in the Far East scientific communities. It is very typical for conclusions to be reached based on three or fewer data points per test with no reference to confidence limits. No wonder there are many conflicting conclusions in the literature! Of course the situation is further confused because of the varying degrees of development of the different materials tested.

Oftentimes researchers screen the specimens and eliminate some of the most valuable specimens from the evaluation. In general, very little data have been accumulated on the characteristic flaws and defects that occur in components. Insufficient information is presented to develop the required understanding of inherent material flaws versus those that are manufacturing and component specific flaws. Yet these specific process induced flaws are often those that initiate failure. In that regard too little feedback has been provided by hardware evaluation programs where, generally speaking, fractographic analysis is inadequate. Therefore, much valuable insight is lost and the technological development of this class of materials suffers accordingly. Existing theories are ordinarily based on rather simplistic views, such as single crack failure initiation.

FORD MOTOR COMPANY RESEARCH ON CERAMIC ROTOR LIFE PREDICTION METHODOLOGY

One of the more systematic and long range studies of ceramic rotor life prediction methodology was conducted by Ford Motor Company Scientific Research Center engineers, DeBell and Swank (1980), Baker et al. (1982), and Govila (1983). During this project, crack growth parameters were estimated via several experimental procedures (e.g., based on stress rate data (flexure), stress rupture data (flexure and tension), and on double torsion data). These data were combined with fast fracture flexure testing for strength, and using finite element stress calculations, failure times for a standard rotor hub were completed. Figures 13, 14, and 15 illustrate in a schematic way how these estimates were accomplished. Figure 16 presents the reliability versus lifetimes and compares these to experimental rotor hub tests.

Ford Motor Company researchers, in their continuing study of ceramic life prediction methodology, completed hot spin testing of contoured rotating disks similar to turbine rotor hubs and designed to fail due to time-dependent mechanisms. Ten disks of hot pressed silicon nitride (HPSN) were tested to failure. Previous experimenters conducted their tests on small parts with very small volumes compared to volumes of typical gas turbine components. Such tests were also conducted at uniform temperatures, but gas turbine components have large temperature gradients. There is a continuing need for generating a time to failure data base on a component the size of a typical gas turbine component with temperature and stress distributions similar to gas turbine components. This data base is useful for evaluation of models of failure and computer programs used to predict time to failure.

A hot spin rig was selected for testing of a gas turbine component because it had accumulated many hours of testing and had shown that it could test turbine disks at speeds and temperatures simulating actual engine conditions.

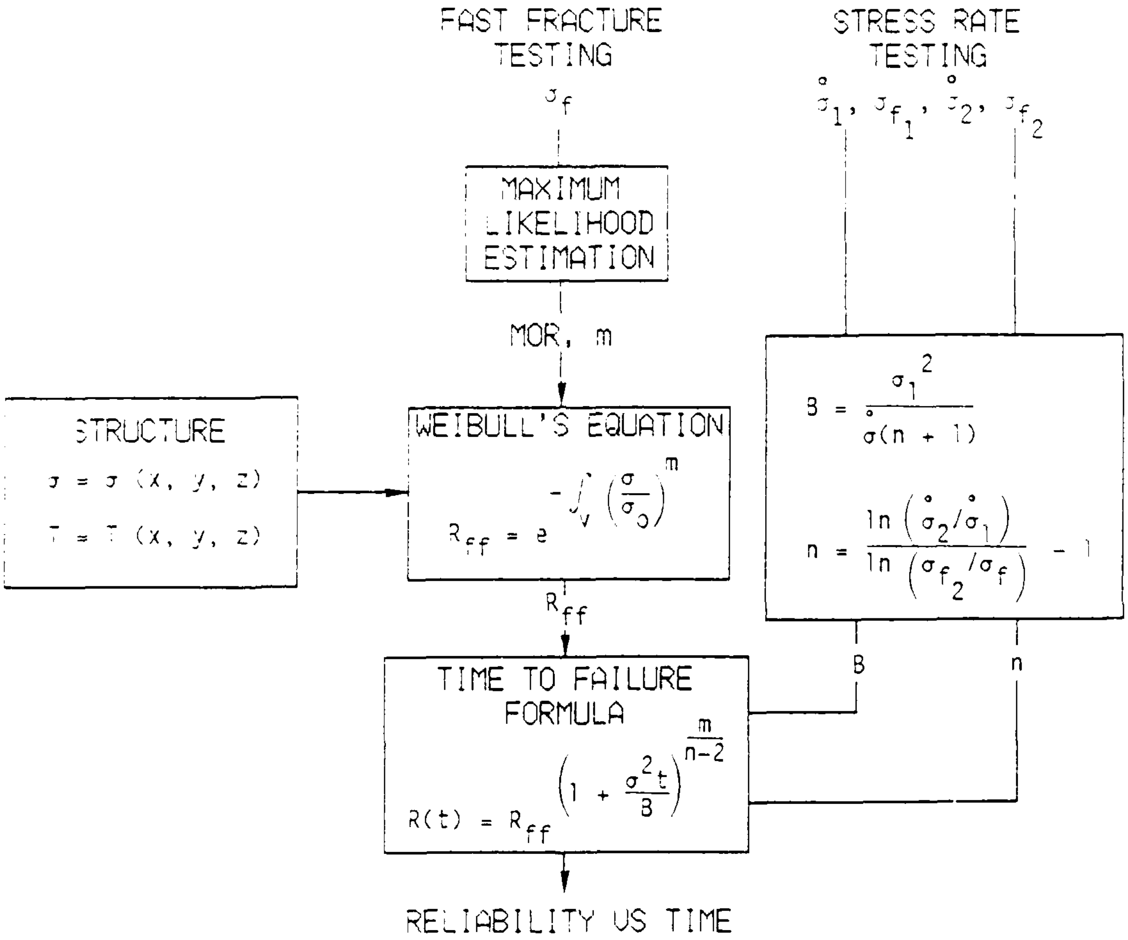

Figure 13. Calculation flow path using stress rate data.

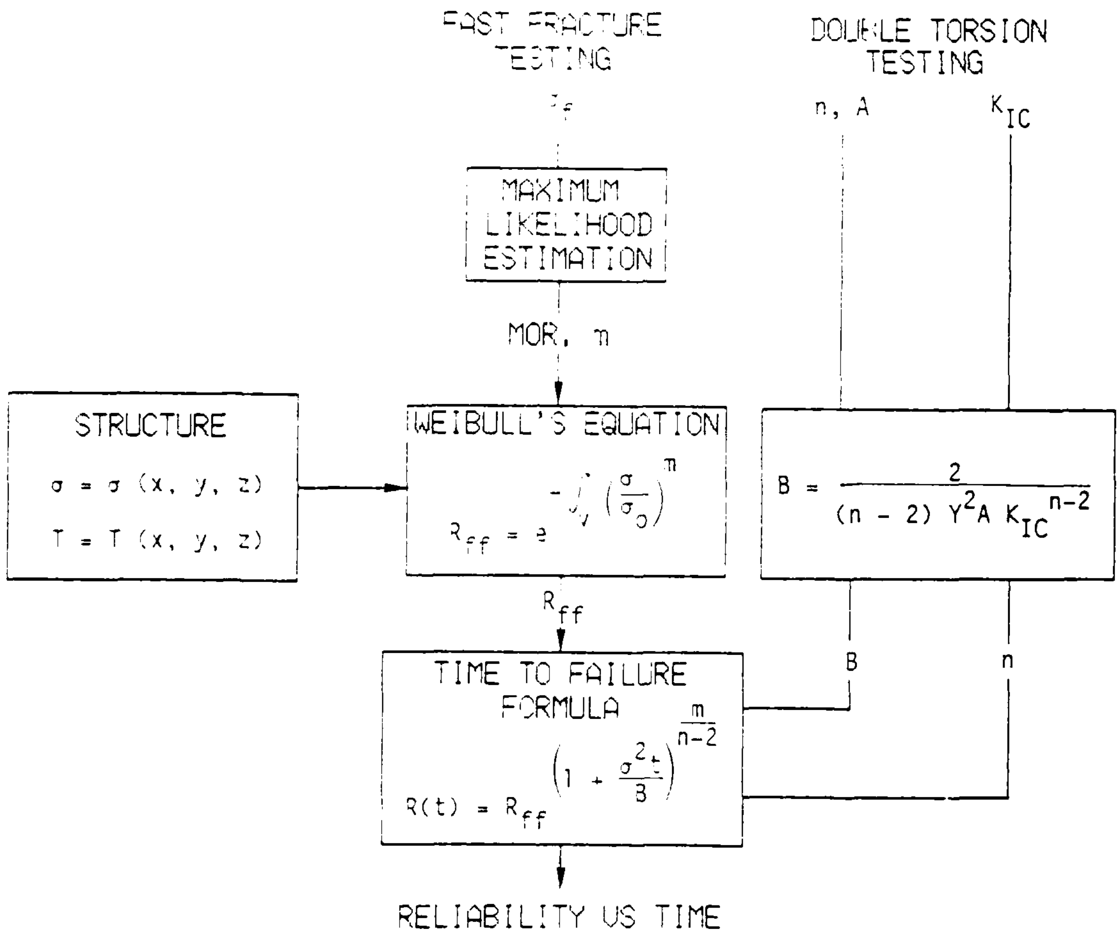

Figure 14. Calculation flow path using double torsion data.

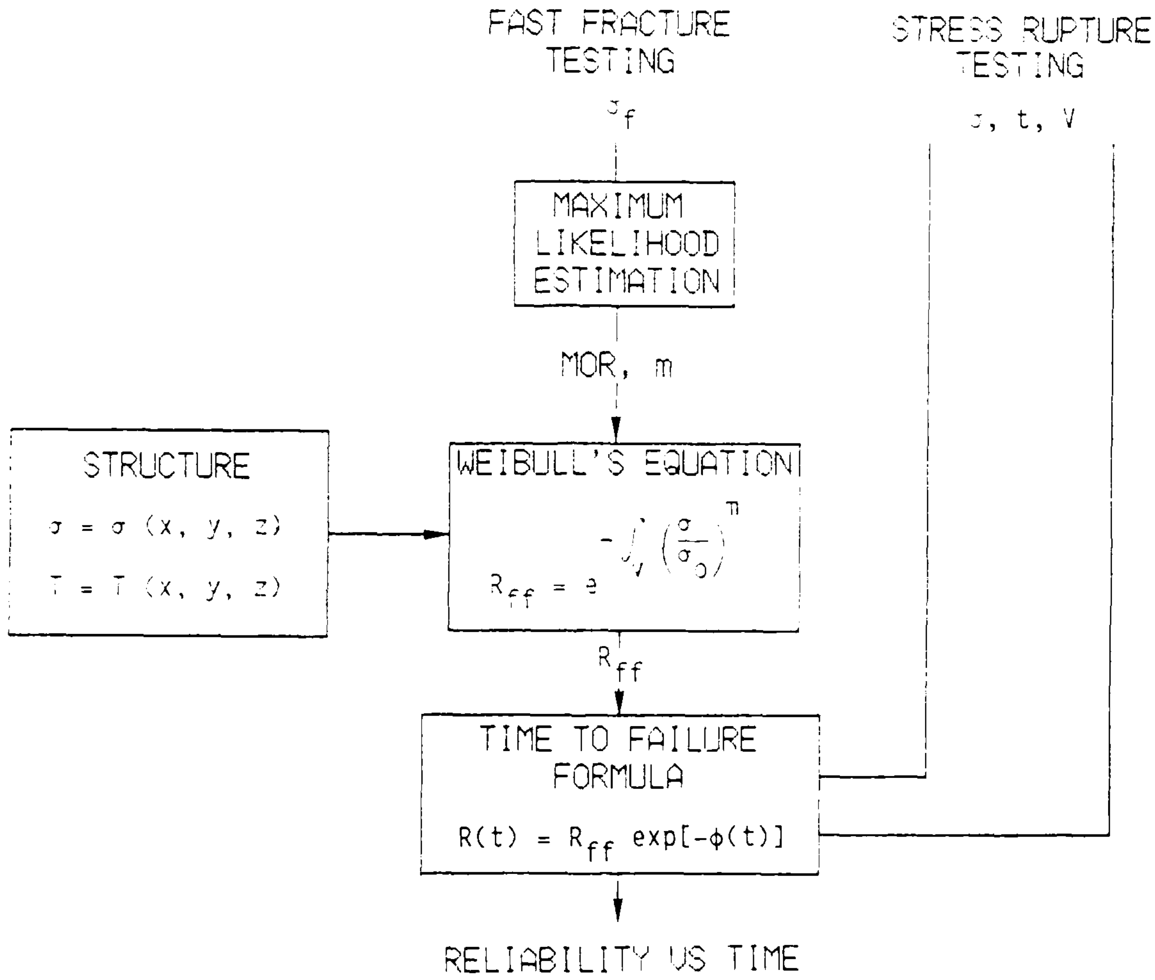

Figure 15. Calculation flow path using stress rupture data.

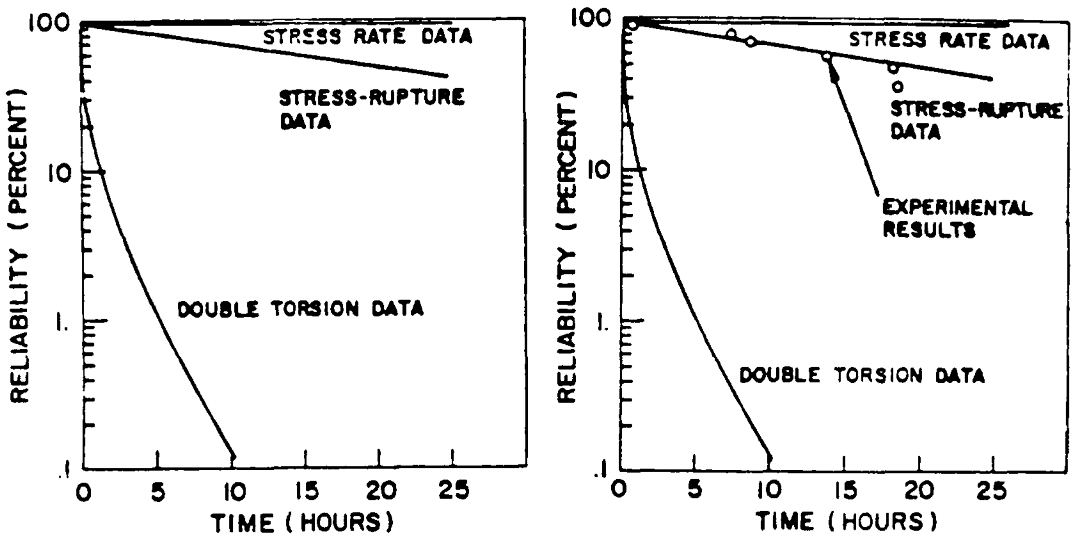

Figure 16. Comparison of hot spin test results to three data base calculations.

Heat was applied to the front face and rim of the spin disk with propane gas burners. The temperature of the front face was measured with a radiation pyrometer and the measured temperatures were used as input to the finite element analysis. The calculated temperature results were compared to experimental data obtained using temperature sensitive paints, and adjustments were made to the model to insure agreement. Subsequently, the temperature distributions calculated from the heat transfer model were used in the stress analysis. Twelve disks were tested in the program, two of which failed on start-up and three disks were considered censored for various times. Three different extensive data bases were used to calculate reliability versus time and the results were compared to the hot spin disk data. The data bases were so-called double torsion, flexure stress rate data, and finally stress rupture data (flexure and tension) (Figures 13, 14, and 15).

Note that in these calculations, two-parameter Weibull models were used and only volume dependency was treated. Alternative approaches to represent materials would be to use area and volumetric dependency, other statistical model representations for the data, or nonparametric models. As for stress calculations, sensitivity analysis of the heat transfer and finite element models and nonparametric data base modeling would be the ultimate refinements for comparison of the results.

Ford results and comparisons are shown in Figure 16, demonstrating the wide range in the various methodologies.

Postfailure analysis on failed hot spin disks has been completed. Components were painstakingly reassembled in an attempt to locate and document failure sites, key crack directions, and fracture initiation origin and sequence of events. Figure 17 is a photo of failed rotors (fragments) and reassembled rotors.

Figure 17. Reassembled rotor 1324.

About 90 percent of the rotor core was reconstructed, 80 percent of the web, and 5 percent of the rim. Failure in components can be characterized by a series of radial cracks that all emanated from either the bore or the teeth. The teeth acted as crack sources for about 90 percent of the cracks. Most cracks could be identified as secondary due to their running into preexisting cracked planes (i.e., like the stem of a T). By backtracking it became evident that a couple of key radial cracks originating at teeth damage were principal cracks. Nevertheless, it was not discerned which was first. All fracture surfaces were carefully examined, including pieces not fitted to the assembly. In no case were time-dependent markings found. Indeed, origin out on the rim seemed exclusively to be secondary impact damage.

Flaw origin mirror analysis again confirmed high stresses were active in the teeth. The stresses may have been as high as 100 ksi, but of course impact or stress concentration due to point loading could account for this. In summary, in these rotor disks, no time-dependent failure origins were discovered. Since the reconstruction was not 100 percent complete, their existence could not be ruled out. Evidence does suggest teeth/bore contact stresses were high, causing radial cracks to form very early in the fracture sequence. Indeed, these may have been the actual source of time-dependent failure. The effort at reconstruction was worthwhile despite the ambiguous results, in that post failure analysis is crucial to truly establish failure mechanisms and validate analytical models. A fact that became very evident was the existence of multiple fracture sites. The schematic of Figure 18 shows eight key crack origins or fractures, and Figure 19 schematically shows the flaws and anomalies detected in four of the rotor hubs. Also shown in Figure 19 are the survival times, e.g., rotor 1319 (24 hours), rotor 1323 (25 hours), rotor 1314 (13.83 hours), rotor 1324 (18.58 hours), etc. Interestingly, five hubs had no indications of flaws, whereas two contained voids and inclusions. Comparing the occurrence of key crack origins and flaws for rotor 1324, there appears to be some correlation. It is interesting to recall that the procedures for life estimating are based on the following equations:

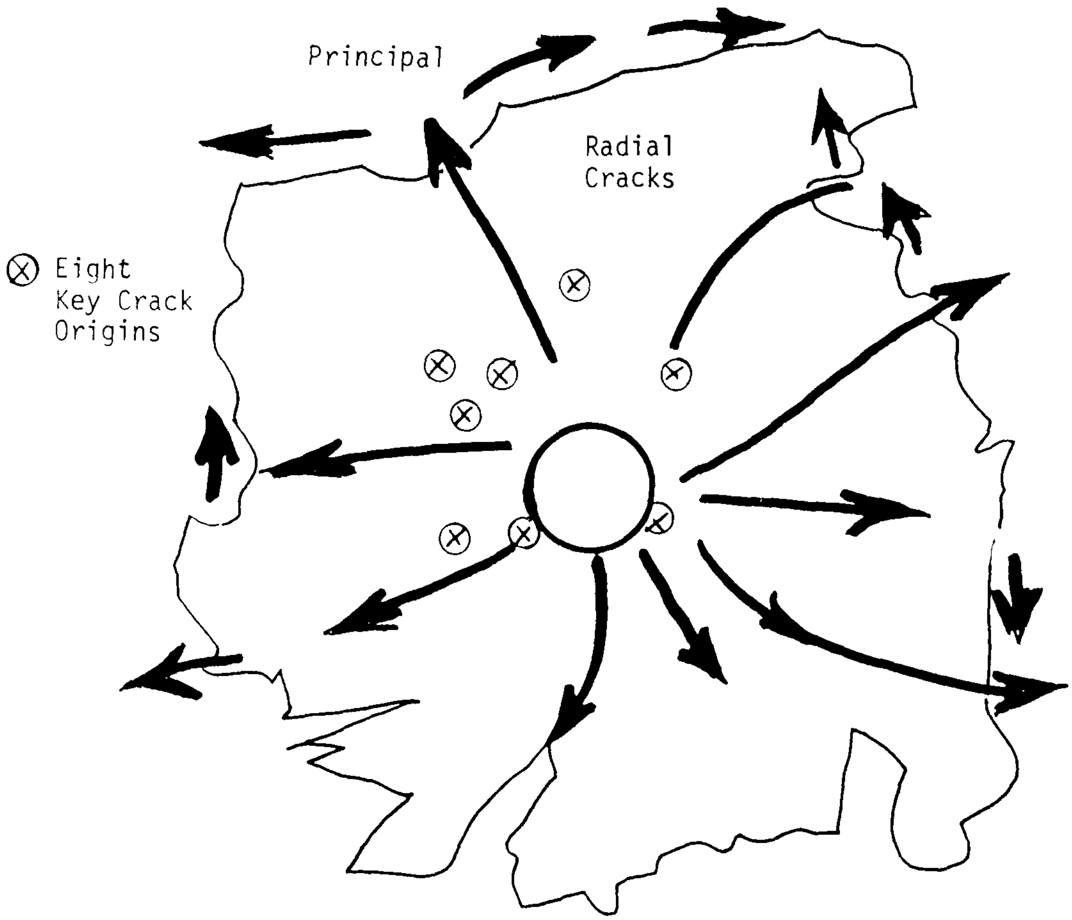

Figure 18. Schematic of failure.

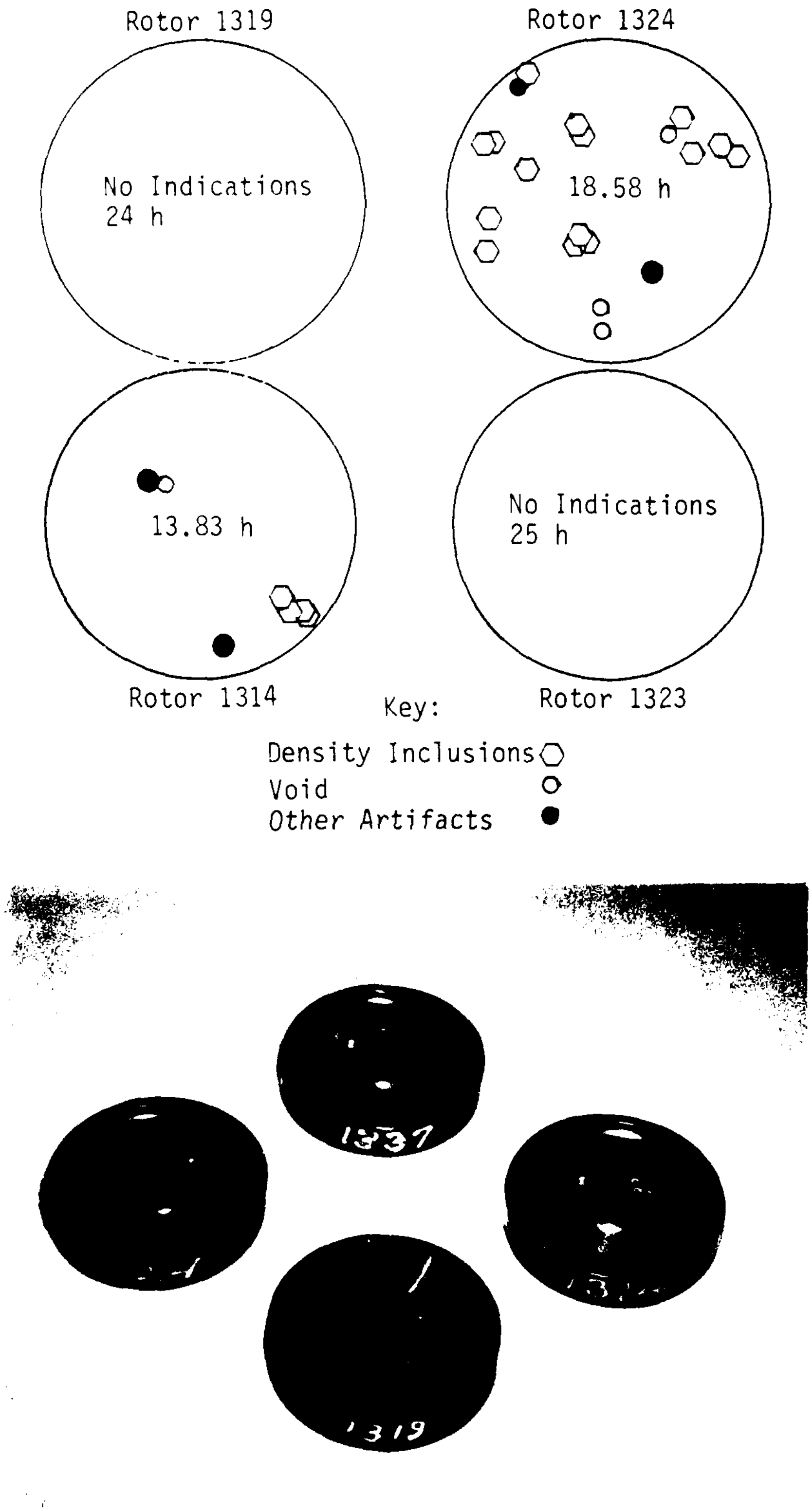

Figure 19. Schematic of ultrasonic and x-ray detection of flaws in rotor hubs.

A. Crack Velocity Based (Double Torsion or Other Method)

$$t = \frac{2\,\sigma_a^{-N}(K_{IC}/\sigma_{IC})^{2-N}}{A\,Y^2(N-2)}$$

where: K_{IC} = critical stress intensity factor

σ_{IC} = strength in an inert environment

Y = geometrical factor

σ_a = applied stress

Then minimum failure time:

$$t_{min} = \frac{2\,\sigma_a^{-2}(K_{IC}\,\sigma_a/\sigma_p)^{2-N}}{A\,Y^2(N-2)}$$

where σ_p is proof stress.

B. Static Fatigue (Creep)

$$t_{min} = \frac{\sigma_a^{-N}(\sigma_{IC}/\sigma_p)^{2-N}\,t_o}{\sigma_{ao}^{-N}}$$

where t_o is the failure time for an applied creep rupture stress σ_{ao}.

C. Dynamic Fatigue

$$t_{min} = \frac{\sigma_a^{-N}(\sigma_{IC}/\sigma_p)^{2-N} \bullet \sigma_o^{N+1}}{(N+1)\,\sigma_o}$$

where σ_o is the strength at a particular stressing rate.

Life estimates for delayed fracture are based generally on two-parameter Weibull models for strength and the following:

Assuming fracture mechanics relation:

$$K_{IC} = \sigma_\alpha \sqrt{\alpha \bullet Y}$$

Slow crack growth phenomena:

$$V = A\,K_1^N$$

Weibull strength distribution:

$$P_f = 1 - \exp^{-V(\sigma/\sigma_o)^m}$$

Then based on the assumption of a single-valued initial crack size contrasted to distribution of cracks:

$$t_f = \int_{a_i}^{a_c} da/V$$

$$a_c \text{ from } K_{IC} = Y\,\sigma_f \sqrt{a_c}$$

Considering the existence of multiple flaws, and based on the observation of actual flaw locations via nondestructive tests, it is obviously possible to make life estimates based on the actual observed flaw condition. Generally speaking, this has not been done on many of the important ceramic development projects. Fracture mechanics based predictions could also be conducted using various representations as listed next, or for that matter nonparametric methods could be applied if sufficient data were available. For example, we could apply the following alternative conventional crack growth equations:

$$V = A(K/K_{IC})^n$$

$$V = A_1(K/K_{IC})\ \exp(n_1\ K/K_{IC})$$

$$V = A_2\ \exp(n_2\ K/K_{IC})$$

The coefficients of these equations can be obtained via various experimental techniques.

FRACTURE IN THE BALLISTIC REGIME

Thus far we have been discussing failure under more or less steady state conditions, albeit under high rotational speeds. It is interesting to briefly consider ceramic fracture under conditions of ballistic impact. Ceramics have long been used as armor materials, but in spite of more than 25 years of analytical and experimental study, relatively little is known about failure and penetration mechanisms during ballistic impact, and particularly the fracture mechanisms.

In the early 1960s modern ceramic armor was developed and found applications in Vietnam as personnel body armor and aircraft armor on helicopters and fixed wing gunships, primarily for small arms threats such as 30- and 50-caliber weapons. Weight reduction was the primary motivation. Currently there is a high level of interest in continued development of ceramic armor. Generally speaking, ceramic armor technology has been largely based on empirical trial methods. Much of the analytical treatment is based on the pioneering work of Wilkins (1967, 1969, 1980). Penetration mechanics codes applied to ceramic armor are still largely derivatives of Wilkins' computer codes. These materials have been evaluated under ballistic impacts with velocities in the 1,000- to 2,000-m/s range. Usually the relative ballistic performance ranking of armor is based on the V_{50} of the material. The V_{50}, ballistic test procedure, can be simply defined as the velocity at which the target will stop 50 percent of the projectiles (U.S. Army, 1984). Other properties that have long been considered as controlling parameters in ballistic impact include tensile strength, hardness, and density.

Recently Mescall and Tracey (1986) incorporated compressive fracture in computer simulations of ballistically impacted ceramic. Their Lagrangian code simulation of ceramic armor targets shows that substantial compressive fields of sufficient magnitude to cause fracture develop prior to the occurrence of destructive tensile stress. Horneman et al. (1984), in their studies of ballistically impacted glass, showed experimentally that flaws are activated as compressive shock waves propagate and then they coalesce. Compressive fracture theory was also developed by Sines and Adams (1978), supported by detailed testing of alumina. Their theory uses a Griffith flaw analysis wherein crack growth occurs due to tensile stress concentrations at a flaw tip. The activated flaw grows only a short distance and arrests as it propagates into the surrounding compressive stress field. Sines and Adams proposed that compressive fracture occurs as a sufficient number of flaws are activated or coalesce. Therefore, their theory proposes that compressive strength is a function of flaw density and distribution and is not dependent on the worst flaw/weakest link theory as in tensile fracture. Lankford (1977), in compressive testing of alumina, showed it is necessary to consider flaw formation in detail. He showed that microplasticity, such as twining under compressive loading, causes microcracks which, in turn, coalesce with other existing flaws, leading to final fracture. Informed sources indicate that detailed fractographic analysis of ceramic ballistic target rubble is being subjected to detailed fractographic studies in the U.S., Europe, Japan, and elsewhere. Scanning electron microscope analysis of such fractured particles shows evidence of flaws in which crack growth and arrest occurred. In ballistic impact the size of flaws initiated can be smaller than in flexure tests, for instance, compressively activated flaws as small as 10 micrometers contrasted to flexural flaws on the order of 100 microns.

Defining fracture modes and relevant properties of ballistically tested ceramics is quite difficult. While quasi-static tensile and compressive fracture modes are fairly well characterized, fractography of ballistic rubble is an emerging art. Part of the difficulty is that initiation and growth of flaws in ceramics varies dependent on the degree of triaxiality of the stress state. Thus, spatial location of flaws and indepth stress analysis are necessary. And, of course, there are also strain rate and shock loading effects on mechanical properties. Thus, changes in crack initiation from static to dynamic loading can minimize the importance of static K_{IC} (fracture toughness) values under ballistic loading. For instance, fracture toughness tests performed under quasi-static conditions (Mescall, 1987) in both silicon carbide (SiC) and titanium boride (TiB_2) indicated that increased K_{IC} combined with lower chemical impurity did not improve ballistic performance. However, a change in fracture mode from trans to intergranular was observed. This appeared to be the result of increased impurities that tended to concentrate at grain boundaries. Cracks propagated in these grain boundaries, and these increased fracture paths led to enhanced ballistic resistance.

It is obvious that ballistic performance is a function of many parameters. Compressive and tensile strengths, density, hardness, elastic moduli, fracture toughness, and chemical purity play important roles. Flaw characteristics are critical in determining fracture modes. Flaw density has been found to relate to compressive strength, and flaw uniformity was an important parameter. Further analytical and indepth experimental studies are required to fully define fracture mechanisms for quasi-static and ballistic impact regimes.

Another major thrust of necessity is to improve characterization, quality control, quality assurance, and nondestructive evaluation techniques. The development of characterization standards and specifications, nondestructive evaluation (NDE), and mechanical test procedures and standards are important. Considering life prediction methodology, it is apparent that continued vigorous efforts are required to truly validate ceramic component predictive methodology.

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SOME NOTES ON SHIP AND HYDRAULIC RESEARCH AND DEVELOPMENT INSTITUTIONS IN THE PEOPLE'S REPUBLIC OF CHINA (PRC)

Justin H. McCarthy

During the past three decades, China has established and equipped an impressive collection of ship and hydraulic research and development (R&D) institutions. Just since 1984, eight major, new hydrodynamic experimental facilities have been completed, giving China the potential for a leading international position in hydrodynamics R&D. This article summarizes observations made during visits to 11 institutions during the late spring of 1987.

INTRODUCTION

This article summarizes the highlights of observations made while visiting 11 of the principal institutions where Chinese ship or hydraulic research and development (R&D) is conducted or administered. My primary focus was on ship hydrodynamics. The official host organization for the trip was the China State Shipbuilding Corporation (CSSC), Beijing. The detailed arrangements for the trip were made by the China Ship Scientific Research Center (CSSRC), Wuxi. I am deeply grateful for the opportunities made possible by leaders of these two organizations.

The institutions visited were:

- China State Shipbuilding Corporation and China Ship Research and Development Administration, Beijing
- Hydraulic Engineering Department, Tsinghua University, Beijing
- Institute of Water Conservancy and Hydroelectric Power Research, Beijing
- Wuhan Institute of Water Transportation Engineering, Wuhan
- Visitors from Ship Development and Design Institute, Wuhan
- China Ship Scientific Research Center, Wuxi
- Naval Architecture Department, Jiao Tong University, Shanghai
- Shanghai Ship and Shipping Research Institute, Shanghai
- Marine Design and Research Institute of China, Shanghai
- Naval Architecture Department, Harbin Shipbuilding Engineering Institute, Harbin
- Naval Architecture Department, Dalian Institute of Technology, Dalian

A few general observations are in order to paint the outward and visible scene in China. Relative to 4 years ago (1983), when I first visited, the general prosperity has improved significantly. Colored clothing is widespread; taxis and other motor vehicles are abundant; and free markets for food, clothing, and household goods have multiplied. Numerous new apartment houses, hotels, and office buildings are under construction in all places visited. Television has extensive advertising, ranging from washing machines to cosmetics. English language instruction is also provided. Many Chinese people are learning English, some in night school. People appear to be well fed, clothed, and of good disposition. Streets and sidewalks are kept surprisingly clean. Public parks and cultural or religious sites are being renovated or restored to attract visitors, Chinese and foreign.

Under the "reforms" being implemented in China, ship R&D institutions are now required to compete with each other for funding. Some appear to have been quite successful, others have suffered. At all institutions there is wonder and sometimes apprehension about what changes in organization and operations will take place in the future under the "reforms." The rules for doing business are changing rapidly. At the operational level, China appears to be functioning in a free-enterprise mode.

CHINA STATE SHIPBUILDING CORPORATION (CSSC) AND CHINA SHIP R&D ADMINISTRATION (CSRDA)

During the morning of 28 May I met with officials of CSSC and CSRDA at a CSSC meeting room located in the northern part of Beijing. CSRDA comes under CSSC, which was founded in 1982 as an "all-China shipbuilding corporation." CSSC combines production with R&D, repair, and trade in both the civilian and military sectors. CSSC reports directly to the PRC "Ruling Council" and is organizationally separate from the Chinese Navy. CSSC administers more than 26 shipyards, 60 marine equipment plants, and 30 research and design institutes, employing about 300,000 people. It not only builds and markets ships and offshore facilities, but also heavy-duty onshore power generation and petrochemical equipment, building materials, heavy machinery, bridges, tunnels, reservoirs, buildings, and electronics equipment. Every PRC shipyard has a "cooperating Japanese partner" and cooperative agreements are in place with Federal Republic of Germany (FRG) and Norwegian establishments. Much equipment is manufactured in China under licenses from overseas.

I was told that the first priority is for the domestic shipbuilding market and secondly for the export market. The domestic needs associated with China's long coastline and very extensive inland waterways are immense. With the exception of liquid nitrogen gas (LNG) and liquid propane gas (LPG) ships, PRC currently manufactures all types of ships to international standards. The recent construction of a 120,000-dwt tanker and plans for a 200,000-dwt tanker were cited, as were launchings of roll-on/roll-off ships, self-unloading ships, and ferries. Oil drilling platforms were stated to be big business items, with repair work done for the United States, FRG, and Singapore. I was told that an American shipowner recently explored the possibility of having a ship hull built at a PRC shipyard, with machinery and outfitting to be done at a Japanese yard. The idea, aimed at reducing hull costs while insuring "high-tech" equipment, was rejected by China.

No predictions were made about the future share of international shipbuilding tonnage in China relative to Korea or Japan. The trend is upward for the PRC share and an increase in world orders for new shipbuilding tonnage is expected beginning in about 1992. Similar expectations have been expressed by Korean and Japanese ship people. I was told that China is preparing to compete more effectively with Korea and Japan with respect to quality as well as price. R&D is being conducted on new ideas and ship types to boost China's competitive posture. Lack of knowledge of international market information was cited as a serious handicap for China.

Three principal priorities for future improvements in Chinese shipbuilding were laid out:

1. **Application of Automation and Robotics.** Developments in this area must be compatible with national development programs, which require full employment. Using Japan as a bench mark, automation is believed mandatory in order to improve efficiency and/or safety and thereby compete effectively. Robotics are being developed for welding of large hull sections and some small sections and also for hull sandblasting and painting. No contradiction is seen between robotics and full employment of workers. A software development center was recently established by CSSC to provide a focus on robotics.

2. **Improved Management Procedures.** New and improved management skills and procedures must be adopted throughout PRC industry in order to improve communication and efficiency. Part of this arises in coping with the "reform" and decentralization process underway in China. It also has to do with data management and computer routing of subcomponents and products. A number of "Administration Institutes" have been established to provide instruction. Perhaps the most important one is at the Dalian Institute of Technology. It includes visiting foreign faculty members, presently including at least one American whom I met briefly while visiting Dalian.

3. **Upgraded Technical Skills.** The general level of technical skills of workers at CSSC organizations must be increased in order for China to be industrially advanced and competent in the "high-tech" arena. The educational effort seems to involve primarily courses of study given at work sites, including programs to allow workers to complete high school. The need for engineers must be enormous because there is now a total of only 2 million university students in China, just 0.2 percent of the total population. Only about one of every 30 to 40 high school graduates is admitted to college. The crippling of universities during the Cultural Revolution compounds the problem.

TSINGHUA UNIVERSITY (HYDRAULIC ENGINEERING)

Prof. Mei Zuyan, head of the Hydraulic Machinery Division of the Department of Hydraulic Engineering, was host during my afternoon visit on 28 May. Tsinghua University (TU) is perhaps the most prestigious engineering and science university in China. After the Cultural Revolution, TU was closed from 1966-70 and not fully reestablished until 1978. Since then, the number of departments has grown from 15 to 25 mainly due to the addition of new science, mathematics, and social science departments. Recent emphasis has been on building up the science side of TU, whereas earlier emphasis had been on the engineering side. TU has about 11,000 undergraduate students, 3,000 graduate students (mainly M.S. candidates), and 5,000 faculty and staff members. In the Department of Hydraulic Engineering, there are about 600 undergraduate students pursuing a 5-year program for the B.S. degree. About 60 and 10 students, respectively, are enrolled in the 2-1/2-year M.S. and Ph.D. degree programs.

Because hydraulics is an "old field," it does not receive as much government research support as other fields such as electronics. Most "research" is applied and supported by factory grants for evaluations of such things as pumps and turbines and by construction company funding for evaluation of soil properties at dam sites. Results of the evaluations are used for M.S. theses. The R&D conducted is primarily experimental; in the machinery area it includes flow diagnostics, cavitation and induced vibration, and solid/liquid two-phase flow pumps. When design problems are diagnosed, fixes are identified, implemented, and evaluated at TU. In order to avoid the high manufacturing costs of bronze blades, a method has been developed to produce plastic resin rotor blades for laboratory evaluations.

Prof. Mei conducted brief tours of the laboratories for hydraulic machinery and soil mechanics, as well as small facilities for teaching. The principal large hydraulic machinery facilities are closed-circuit cavitation test stands for water turbines and pumps and an open-flume test stand for turbines. The cavitation facility has a vertical resorber divided into four quadrants. All of these facilities were in operation during my visit and appeared to be neat and well maintained and were supervised by competent and energetic individuals. In a small flume a group of students was measuring velocities in a boundary layer on a flat plate using a one-dimensional laser Doppler velocimeter built at TU. In the soil mechanics laboratory I was shown a static/dynamic triaxial soil testing machine recently purchased in the United States. The machine allows simultaneous torsional and tensile loading of soil samples, a novel feature that does not work properly despite the high cost of this feature. TU is attempting to have the supplier correct the problem and is clearly upset about the situation.

The Department of Hydraulic Engineering at TU signed agreements of cooperation in 1985 with the Iowa Institute of Hydraulic Research, University of Iowa, and Trondheim University in Norway. Three departmental faculty members are members of the Chinese Academy of Science.

INSTITUTE OF WATER CONSERVANCY AND HYDROELECTRIC POWER RESEARCH (IWHR)

My host at IWHR during the morning of 29 May was Prof. Jin Tailai, senior research engineer at the Department of Hydraulics. He also serves as professor at the Wuhan Institute of Hydraulic and Electrical Engineering. At IWHR I was greeted by Li Guifen and Gao Jizhang, respectively, the head and deputy head of the Hydraulics Department at IWHR. The institute was established in 1958 by merging three existing institutes. It was disbanded in 1969 and reorganized in 1978 under the Chinese Academy of Sciences. The institute employs about 1,500 people of whom about 900 are scientific and technical personnel, including about 100 senior engineers. IWHR is one of the principal institutions of its type in China and conducts investigations on a wide range of topics: high dam hydraulics and structures, sedimentation, water resource development and utilization for agriculture and power plant cooling, and blasting. The institute provides extensive in-house staff training courses and has M.S. and Ph.D. degree programs that have enrolled about 25 percent of the professionals.

The principal project underway at IWHR concerns the proposed Three Gorges Dams for the Yangtzse River, which are expected to generate more than 15,000 MW of electricity. The investigation is part of a national effort currently in the feasibility stage. Work was initially begun before 1966 and halted during the Cultural Revolution. If the feasibility studies are positive, construction is expected to be completed by about 2010. Sedimentation problems are of major concern and are being evaluated in large-scale river bed simulations I viewed at IWHR. Two dams are being considered, with heights of perhaps 200 meters and 150 to 180 meters, giving rise to potentially very serious cavitation erosion problems in the water turbines and on the dam spillways. Two impressive new cavitation facilities have recently been built to address these problems. One has ship applications. Neither facility had been placed in operation prior to my visit.

Prof. Jin showed me several of the facilities at IWHR: cavitation tunnels, hydraulic machinery laboratory, computing center and, as already mentioned, the large-scale, housed sedimentation model of the Yangtzse River.

High-Speed Cavitation Tunnel

This is a closed-jet facility with a square test section 30 by 30 cm, 200 cm in length, and is expected to have the exceedingly high maximum speed of 35 m/s (Figure 1). It is powered by a 1,250-hp General Electric motor that drives a Worthington two-stage pump. It is equipped with a novel horizontal resorber that can be short-circuited by operation of an enormous flapper valve located in the resorber. The facility was designed for high-speed cavitation research, for example on water turbine blade cascades, and could be applied to ship research.

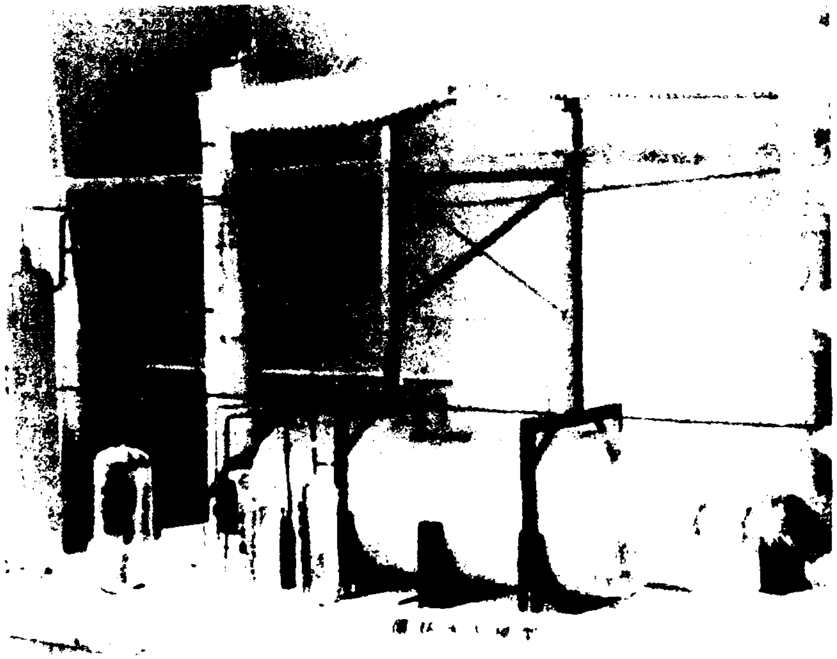

Figure 1. Model of high-speed water tunnel: maximum velocity 35 m/s.

The facility was completed in 1986 and will be placed in operation in 1988 when power supply circuits have been put in place to handle the very large electrical load. Dynamometry and other measurement equipment will be procured in the future.

Spillway Cavitation Channel ("Vacuum Tank")

This is also a new facility, scheduled to be operated for the first time in July 1987. It has a test section about 4 meters high, 1 meter wide, and 17.5 meters long. It is a closed-circuit flow channel designed for cavitation tests of 2-meter-high concrete spillway models at a maximum flow rate of 0.6 m^3/s. Construction of this facility and the high-speed facility was done by a Beijing contractor, using designs developed at IWHR. The appearance of both facilities was excellent.

Hydraulic Machinery Laboratory

This laboratory serves the same purpose as its counterpart at Tsinghua University. It is used primarily for experimental evaluation and redesign of hydraulic pumps and turbines. It boasts China's largest pump dynamometer, which was manufactured in FRG. It also has a very large weighing tank used for numerous routine calibrations of magnetic flow meters, a service similar to that performed by the National Bureau of Standards in the United States.

Computing Center

The institute has two central computers, one manufactured in Japan, a Hitachi M-160H, which is about 5 years old. The other was manufactured in the United States, an IBM 4381, which is 1 year old. Data analysis and theoretical calculations are conducted on these computers.

WUHAN INSTITUTE OF WATER TRANSPORTATION ENGINEERING (WIWTE)

On 31 May and 1 June I stayed at WIWTE, which is primarily an educational institution specializing in engineering for vessels operating in restricted river and coastal waters. It grew from a Maritime Vocational School founded in 1946 and comes under the Ministry of Communications. Prof. Wu Xiuheng, vice president of the institute, was my host. There are seven departments with about 3,000 students and a teaching staff of about 1,000, of which 600 have professional degrees. The B.S. degree takes 4 years to obtain, and the M.S. degree takes 2 or 3 additional years. R&D conducted at WIWTE is very applied and is about 75 percent on riverboats with the remainder primarily on ships for coastal waters. The institute was essentially shut down from 1966-73. Prof. Wu and his colleagues conducted a tour of five of the principal facilities at WIWTE, which is a member organization of the International Towing Tank Conference (ITTC).

Following the tour, at Prof. Wu's request, I gave a seminar to about 20 faculty members of the institute. Questions at the end mainly concerned practical items such as how to analyze twin-screw propulsion data and how to measure propeller duct thrust. There was interest in methods to compute thrust deduction and wake fraction, the latter problem being only partially solved anywhere.

Ship Model Towing Tank

This facility began construction in 1979 and was opened in 1984. It is a medium size tank: 132 meters long, 10.8 meters wide, and has an adjustable depth that varies between 0.2 and 2.5 meters to an accuracy of ± 3 mm. Maximum carriage speed is 6 m/s. I was told that more than 100 models (or variants) are tested each year. The models are usually constructed of wood and are typically 2.5 meters in length. A large amplitude (± 2 meters) planar motion mechanism (PMM) is under construction for maneuvering experiments. Nearly all of the models on display were of shallow draft vessels, most of them being twin screw with the propellers mounted on twin skegs of considerable length. Much of the experimental work focused on testing variants of the twin skeg designs to optimize powering performance. Conventional ducted propulsors were sometimes used. Tandem propellers had been tried but no work had been done on vertical axis propellers, which have been used in other countries for shallow water applications.

Outdoor Maneuvering Basin

This is a large rectangular basin 60 by 80 meters with a maximum adjustable water depth of 1.5 meters. Radio-controlled model maneuvering experiments are conducted in this facility. City water is used and a storage tank is available when the basin's water level is lowered. Neither this basin nor the tow tank is fitted with a wavemaker. An older, smaller tow tank, which I did not visit, has a wavemaker.

Circulating Water Channel

A circulating water channel with a horizontal circuit was completed in 1984. It has a test section 0.9 by 1.8 meters, 6 meters in length, and a design water speed of about 1.8 m/s. This facility is heavily employed. It is used for propeller open water tests, rudder torque measurements, and PMM experiments.

Wind Tunnel

This facility is of the open-jet type with a 1-meter-diameter jet 1.5 meters long. During the visit wind forces and moments were being measured on a ship model attached to a ground board. Experiments have recently been conducted on a sail fitted, as an auxiliary propulsor, to a model of a 5,000-ton ship used on the Shanghai-Tokyo route.

Structures Laboratory

This well-maintained laboratory contains a number of large dynamic and static structural loading test beds. During the visit stress concentrations on the cross structure of a 1/10-scale model of a catamaran ferry were being evaluated. This work was supported by the Chinese Ship Classification (Insurance) Society.

WUHAN SHIP DEVELOPMENT AND DESIGN INSTITUTE (WSDDI)

During the afternoon of 1 June I was visited in my WIWTE guest house rooms by two representatives of WSDDI. WSDDI reports to CSSC through CSRDA and employs about 1,500 people who do all aspects of ship design for both naval and oceangoing merchant ships. WSDDI prepares working drawings for ship hull, machinery, and electrical systems and is working hard to obtain design work in the face of intense competition from other design agencies in Shanghai and Beijing.

Ship stability was cited as an important issue following the capsizing of a ferry in Harbin on the Songhua River in 1986, with the deaths of more than 100 people who gathered on one side of the ferry to observe a fight. Catamaran hulls are being investigated for enhanced stability. I was asked for my view on twin skeg hull configurations, which are being designed at WSDDI and tested at WIWTE and CSSRC. In brief, they have poor propeller inflow, potential propeller-induced vibration problems, high wetted area (and resistance), and large turning radius; they do, however, have good directional stability characteristics.

CHINA SHIP SCIENTIFIC RESEARCH CENTER (CSSRC)

I spent 2 days, 3–4 June, at CSSRC in Wuxi. On the first day I was briefed on CSSRC by Prof. Dong Shitang, director, and Prof. Gu Maoxiang, honorary director, visited selected facilities, and gave a seminar to about 50 staff members. During the afternoon of the second day discussions were held with the two directors. CSSRC comes under CSSC through CSRDA and conducts both merchant and naval ship R&D in the hydrodynamics and structures disciplines. In these two areas, for naval ships, CSSRC is the Chinese counterpart to the David Taylor Naval Ship Research and Development Center (DTNSRDC) in the United States.

The facilities at CSSRC were put into operation beginning in 1965. Wuxi was chosen as the closest location to Shanghai having a granite foundation to support the massive facilities designed for CSSRC. The original staff of CSSRC came from smaller test facilities in Shanghai that are now part of the Marine Design and Research Institute of China, Shanghai. About 1,300 people are employed in Wuxi and another 300 in Shanghai where a branch exists; about 150 staff members out of a total of 800 professionals are considered to be senior researchers. CSSRC has an in-house academic program for M.S. and Ph.D. degrees. One of Prof. Dong's recent Ph.D. recipients will do postdoctoral research in the United States beginning in the fall of 1987.

Three of CSSRC's most important research areas in ship hydrodynamics at the present time are: (1) the physics of cavitation inception, erosion, and noise; (2) theoretical/numerical modeling of developed cavitation on propeller blades and associated induced shaft and hull vibration; and (3) methods to treat nonlinear hydroelastic problems in ship seakeeping.

CSSRC is a member institution of ITTC.

Towing Tank

Completed in 1965, it is 474 meters long, 7 meters deep, 14 meters wide for a 175-meter-long center portion, and 7.5 meters wide at the ends; maximum carriage speed is 15 m/s. The towing tank has a cantilevered top over the wide central portion. Paddle-type wavemakers are located at one end of the tank. Models of hydrofoil craft, as well as merchant ships, were on display near the tank.

Cavitation Tunnel

Opened in 1973, this facility closely resembles the cavitation tunnel at British Marine Technology in Feltham, U.K., including the resorber. It has a closed-jet test section 80 cm in diameter and 3.2 meters long, with a maximum velocity of 20 m/s. Model propellers investigated include wide-bladed types, propellers with moderately skewed blades, and ducted propellers.

Seakeeping Basin

Opened in 1971, this facility is similar to the DTNSRDC seakeeping basin. It is 69 by 46 meters with a depth of 4 meters. It has the same pneumatic-type wavemakers on two sides, bridge and carriage, as built at DTNSRDC around 1960. Two SWATH models, which had been tested extensively, were beside the basin. SWATH research had been completed but no plans had been made to build a SWATH ship.

Rotating Arm Facility

Constructed in 1968, this facility also resembles a DTNSRDC facility. The basin is 48 meters in diameter and 4.5 meters deep; the rotating arm has a maximum angular velocity of 1 rad/s.

SHANGHAI JIAO TONG UNIVERSITY (JTU) (NAVAL ARCHITECTURE)

I visited JTU during the afternoon of June 5, hosted by Prof. Sheng Chen-Pang, vice president of JTU and director of the Ship Hydrodynamics Laboratory, together with Profs. Miao Guoping, Jin Xianding, and Yang Shugang. The university, founded in 1896 as Nan Yang College, is one of the older science and engineering universities in China. It currently has about 11,000 students and 5,600 staff members. A second campus is being built about 20 km from the present location to allow the enrollment to rise to 15,000 students with a staff of 7,000. The new campus will house the applied science faculties and freshman and sophomore activities for other departments. A new library, the largest at a Chinese university, was opened in 1985. A computer center was established in 1980 and houses a number of U.S.-manufactured machines. Research activities are emphasized at JTU. Cooperative programs exist with U.S. universities, notably the Massachusetts Institute of Technology (MIT) and University of California at Berkeley, whereby Ph.D. candidates can do their course work at JTU and their dissertations abroad, receiving the Ph.D. degree from JTU. Other Chinese institutes I visited would like to establish similar programs.

The Department of Naval Architecture and Ocean Engineering enrolls about 100 undergraduates each year for its 4-year B.S. course, 30 graduate students per year for its 2-year M.S. course, and 10 students per year for the 3-year Ph.D. program. Students may specialize is one of five areas: hydrodynamics, ship or offshore structures, design, or construction. Prof. Sheng said that the department receives excellent funding support for its R&D activities from multiple sources including the Ministries of Education and Transportation and China's National Science Foundation. JTU is a member organization of ITTC.

Towing Tank

Opened in 1958, the tank is 110 meters long by 6 meters wide and 3 meters deep, with a maximum carriage speed of 6 m/s. It is equipped with a plunger-type wavemaker having computer-controlled irregular wave capability. Most of the models nearby, 2 to 4 meters in length, were of coastal and inland water vessels, many of the twin-skeg, twin-screw variety. Prof. Sheng does not believe that surface tension effects are important in his tank, based on model/full-scale powering performance correlations done at JTU..

Cavitation Tunnel

Opened in 1978, the tunnel has a 0.6-meter-diameter closed-jet test section that is 2 meters long. Maximum tunnel water speed is 15 m/s. The tunnel is operated only during the morning due to restrictions on electrical power supply. Propeller models, typically 0.3 meter in diameter, are manufactured by hand; Kempf and Remmers (FRG) measuring equipment is available to check manufacturing accuracy. Screens are used to simulate ship wake flow to propellers. No equipment is available for laser Doppler velocimetry or microbubble measurements. Profs. Jin and Yang are conducting a joint experimental/theoretical-numerical investigation on propeller/hull interaction, using the cavitation tunnel for the experimental phase of the work.

Other

A university swimming pool is sometimes used for radio-controlled model maneuvering experiments. A special layout has been installed on the ground floor of the cavitation tunnel building to allow simulation of the maneuvering performance of ships in the channel leading to a lock of the proposed Three Gorges Dam, together with evaluation of the lock itself when raising or lowering a ship from or to the channel.

SHANGHAI SHIP AND SHIPPING RESEARCH INSTITUTE (SSSRI)

The visit to SSSRI, down the Huangpu River in eastern Shanghai, during the morning of 8 June was hosted by Huang Zhongxiu, director, in company with Chen Daquan, vice director for Hydrodynamics, and Guo Yong Song, manager of the cavitation tunnel. SSSRI, under the Ministry of Communications, was founded in 1962 to conduct R&D on merchant ship hydrodynamics and structures, marine diesel engines, automatic controls, and navigational aids. The institute has extensive experimental facilities and is a member of ITTC. It employs about 1,200 people, half of whom are engineers or technicians.

In discussions I was told tandem propellers had been designed and tested at SSSRI for backfit to a tanker. Although reportedly having good powering and cavitation characteristics, the tandem propellers were never built. I was told that most propellers are "designed" from propeller charts because more sophistication is unwarranted in view of the poor knowledge of full-scale wake flow to the propeller.

Towing Tanks

There are two towing tanks, the older and smaller one being 50 meters long, 6 meters wide, and 2.2 meters deep, with a maximum carriage speed of 3 m/s. It is used for shallow and restricted water experiments and has a plunger-type wavemaker for regular waves. The newer, larger tank opened in 1984; it is 192 meters long, 10 meters wide, and 4.5 meters deep and has a maximum carriage speed of 8 m/s. It has a flap-type wavemaker and can generate irregular waves. Many shallow draft model hulls were in evidence; a catamaran hull for use as a ferry in Guangzhou was also present.

Circulating Water Channel

The cross section is 1.5 by 1.0 meter with a length of 6 meters; maximum water speed is 2 m/s. This facility is used for flow visualization about model hulls, open water propeller tests, and rudder and offshore platform load experiments.

Cavitation Tunnel

This is of Kempf and Remmers (FRG) design with a square test section of about 0.6 by 0.6 meter. It was opened in 1984 and has a second, much larger test section for inserting 4-meter hull models. There is an inclined shaft dynamometer for propellers also built by Kempf and Remmers. Model propellers are made by hand and appeared to be of high quality.

MARINE DESIGN AND RESEARCH INSTITUTE OF CHINA (MARIC)

Shen Qixin, director of the Ship Hydrodynamics Laboratory and deputy chief naval architect, was host during my visit to MARIC on the afternoon of June 8. Mr. Shen spent 2 years, 1982-84, working on theoretical hydrodynamics problems at the Netherlands Ship Model Basin in Ede-Wageningen. MARIC, founded in the early 1950s, and the precursor of CSSRC in Wuxi, employs about 1,900 people of whom about 1,000 are engineers or assistant engineers. About

110 people work in the Ship Hydrodynamics Laboratory, including a team that conducts sea trials. MARIC advertises itself as a comprehensive design institute specializing in R&D of ships and offshore structures. It has conducted R&D on more than 500 ships, including some naval auxiliaries, and is a member of ITTC.

MARIC is an agency of CSRDA, and like other organizations, the Hydrodynamics Laboratory must compete for design and R&D contracts. About 50 percent of the support comes from other sections of MARIC with the remainder coming from elsewhere, and not necessarily from the hydrodynamics arena. One recent project considered was the design of a kiddie train for a Beijing botanical garden. The adverse impact of the world shipbuilding slump on China has been felt at MARIC as elsewhere.

Mr. Shen conducted a tour of all the hydrodynamic facilities, which were in excellent condition. Each had its own dedicated computer for data collection and analysis.

Towing Tank

Built in 1953, the tank is 70 meters long, 5 meters wide, and 2.5 meters deep; maximum carriage speed is 7 m/s. The carriage is unmanned, riding on a single rail that is cantilevered above the centerline of the tank, similar to the arrangement at Davidson Laboratory of Stevens Institute of Technology. A plunger-type wavemaker is installed. One recent investigation involved placement of a duct ahead of and above the centerline of the propeller on a full form tanker to accelerate flow to the upper part of the propeller. Up to a 5-percent increase in propulsive efficiency and improved cavitation performance were realized with the duct in place.

Cavitation Tunnel

Built in 1958, the tunnel resembles one at the Netherlands Ship Model Basin with bifurcated downstream legs. It has a square test section (with rounded corners) 60 by 60 cm, 2.8 meters in length; maximum water speed is 7 m/s.

Maneuvering Basin

Opened in 1958, this outdoor basin is 64 by 63 meters in planform and has an observation tower on one side. No wavemakers are installed. The tank is used for radio-controlled model maneuvering tests.

Wind and Wave Current Tank

This is the newest and most complex facility at MARIC, built in 1985 and not yet fully operational. It consists of a tank 3.2 meters deep, 12 by 28 meters in planform, with flap wavemakers on two sides. Current is generated by pumping water from one end of the tank via a side channel to a screen-covered slot spanning the bottom of the other end of the tank. Wind is generated by three fans mounted on a fixed platform in the tank. This facility will be used primarily for R&D on offshore structures. Figure 2 is a schematic of the tank.

Wind Tunnel

This facility, built in 1959, has an open-jet octagonal test section 1.5 by 1.5 meters, 1.7 meters in length; maximum speed is 40 m/s. It is equipped with a three-component balance for measuring lift, drag, and moment. Experiments were recently performed on a host of two-dimensional shapes, but the data have not been published.

1. Wave Maker
2. Current Generator
3. Wind Blower
4. X-Y Carriage
5. Beach
6. Current Nozzle
7. Current Channel
8. Pit (depth 3.0 m)

Figure 2. Wind wave and current tank.

HARBIN SHIPBUILDING ENGINEERING INSTITUTE (HSEI)

I stayed at the HSEI guesthouse on 9–10 June, hosted by several people at different times: Prof. Zhu Dianming, chairman of the Science and Technology Commission of Heilongjiang Provincial Government; Prof. Wu Deming, vice president of HSEI; Prof. Li Jide, chairman of the Naval Architecture Department; and Prof. Huang, who specializes in theoretical hydrodynamics. After visiting the experimental hydrodynamics facilities of HSEI, I gave a seminar to about 20 faculty members. I was asked technical questions concerning methods to compute ship wavemaking resistance and characterization of ocean environment.

HSEI, founded in 1953, has nine departments offering shipbuilding-related engineering courses, ranging from naval architecture to electronic engineering. There are about 3,000 undergraduate and 400 graduate students with a staff of about 900, of whom more than 100 are professors or associate professors. HSEI is authorized to grant Ph.D. degrees in ship hydrodynamics and underwater acoustics. It comes under CSSC (CSRDA) and has close ties with CSSRC. Prof. Zhu is anxious to establish links with western institutions, where he would like to place visiting researchers, and has travelled extensively in the United States and Western and Eastern Europe to this end. HSEI will soon apply for ITTC membership.

Prof. Huang is doing theoretical research on Guilloton's method for computing ship wavemaking resistance as a simple alternative to more elaborate methods. Prof. Huang said that a number of other workers were attempting to implement Dawson's method (DTNSRDC) but were hindered by the large computing times required.

Towing Tank

A new towing tank will be opened on 1 October 1987. The tank is 108 meters long, 7 meters wide, and 3.5 meters deep. Only carriage rail alignment and installation of a wavemaker remain to be completed. The wavemaker has been designed and manufactured in Denmark at a cost of $550,000 and will be installed by the Danes. It consists of seven paddle-type wavemakers that can be programmed to generate irregular waves. A second older and smaller towing tank was not visited; its dimensions are 25 by 3 by 2.5 meters.

Circulating Water Channel

This very heavily used facility has a test section 1.5 by 1.7 meters, 7 meters in length; maximum water speed is 2 m/s. It has been used for all sorts of experiments, many of which would normally be conducted in a towing tank, such as ship and submerged body resistance, open water propeller tests, planar motion mechanism tests on submerged bodies, and flow visualization. About eight models, some with bow and stern variants, are constructed and tested each year.

DALIAN INSTITUTE OF TECHNOLOGY (DIT)

I stayed at the DIT guesthouse on 11-12 June and was hosted by Prof. Jiang Ji-Sheng, director of the Naval Architecture Institute, together with Prof Wang Yan-Ying, his deputy director. Prof. Jiang attended the University of Michigan and worked in the aerodynamics field in the United States for a number of years during the late 1940s.

Founded in 1949, DIT is one of the most important science and engineering universities in China. It has 11 departments and a National Center for Industrial Science and Technical Management Development, established in 1980 with U.S. Department of Commerce cosponsorship, as a major subcomponent of the institute for training managers (mentioned earlier in this report). There are presently about 8,000 undergraduate students, 1,500 graduate students, and 1,000 evening students at DIT with about 2,000 faculty members, 600 of whom are professors or associate professors. The Naval Architecture Department currently admits 70 students each year to its 4-year B.Sc. degree program. It offers courses in ship hydrodynamics, structures, and marine engines. The Department of Civil Engineering, rather than the Naval Architecture Department, offers courses on ocean engineering and has an associated laboratory.

Following a tour of DIT facilities I presented a seminar to about 25 faculty members and a few graduate students with Prof. Jiang as interpreter. Later Prof. Wang and three of the younger faculty members described their current research interests. Shen Hua, who has studied at the Danish Technical University in Lyngby, told of his work on boundary integral methods for potential flow problems, mainly confirming numerical results obtained by previous investigators. Wang Dazheng has specialized in propeller theory and has developed his own computer codes for doing propeller calculations. He hopes to study propeller theory in the United States at either MIT or the University of Michigan. Finally, Huang Zhenjia briefly described his theoretical work on nonlinear ship stability and capsizing.

Towing Tank

This facility was opened in 1986; it is 160 meters long, 7 meters wide, and 4 meters deep. It is equipped with both gravity and strain-gage resistance dynamometers, and future plans call for acquisition of a wavemaker and planar-motion mechanism. About 10 models were built and tested in the first year of operation, one of which was a SWATH design. DIT will soon apply for ITTC membership. Figure 3 shows the towing tank under construction.

Flume

The facility is about 50 meters long with a cross section about 1.5 by 2.5 meters. It is equipped with a wavemaker and fans for wind generation and produces a current via a return grating and a duct with pump under the flume. A recent M.S. thesis reported force measurements on segmented two-dimensional structures of interest in ocean engineering.

Wave Basin

This basin is about 60 by 60 meters with a 0.8-meter water depth. It is equipped on two sides with paddle-type wavemakers and ad hoc fans and pumps for generating wind and currents. During my visit an experiment was underway to measure cable and fender forces produced by a large ship model adjacent to a dock.

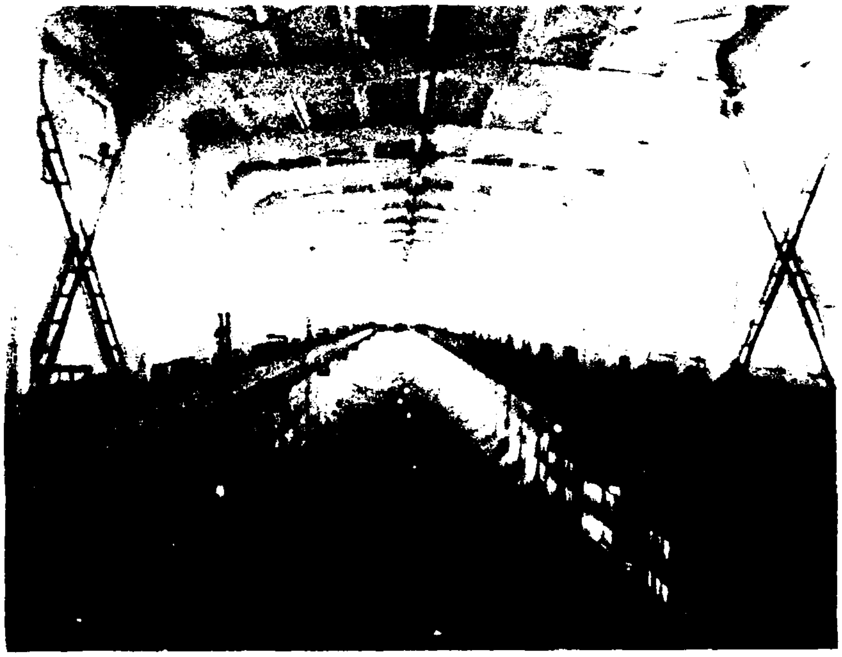

Figure 3. The towing tank under construction.

SOME CONCLUDING REMARKS

Research being conducted was generally of an applied nature, and when fundamental, it was often of the "catch-up" rather than "cutting-edge" variety. Researchers and professionals were uniformly competent and enthusiastic about their work.

I visited six ship hydrodynamic experimental facilities that have been opened since 1984 and two that will be operational by early 1988. These included four large towing tanks with lengths between 108 and 192 meters located, in order of ascending length, in Harbin, Wuhan, Dalian, and Shanghai; two new, first-class cavitation tunnels in Shanghai and Beijing; a circulating water tunnel in Wuhan; and a wind/wave/current tank in Shanghai. These new facilities, together with existing facilities, give China a ship hydrodynamics research, development, test, and evaluation (RDT&E) capacity, or potential, that is exceeded only by that of Japan. China has clearly made a major commitment to development of in-house underpinnings for its shipbuilding industry.

Despite the impressive new facilities, it is not clear that sufficient R&D support is being provided in order for China to be able to compete in the near term on the international shipbuilding market with Japan or Korea; the latter is rapidly emerging as the world's leading shipbuilding nation. No one I spoke with was willing to make predictions about China's full-blown entrance into the international shipbuilding market.

Justin H. McCarthy is on leave from the David Taylor Naval Ship Research and Development Center, where he was head of the Naval Hydromechanics Division and technical manager of the Navy's Propulsor Exploratory Development Program. He will be on assignment with ONRFE until November 1987. His professional interests include propulsor hydrodynamics, drag reduction, and computational fluid mechanics. Mr. McCarthy is a member of the Advanced Planning Committee of the Society of Naval Architects and Marine Engineers, an associate editor of the Journal of Ship Research, *and recently served for 6 years as chairman of the Resistance Committee of the International Towing Tank Conference.*

ADVANCED TELEROBOTIC SYSTEMS UNDER DEVELOPMENT IN JAPAN

Donald K. Moore, Hugh Spain, William R. Uttal,
Steven F. Wiker, and Sachio Yamamoto

A number of leading Japanese academic, industrial, and government research institutes were visited to observe firsthand the existing state-of-the-art of Japanese technologies in advanced telerobotics and supporting systems. At Sony's Atsugi Research and Development (R&D) Center, a high definition video system was demonstrated. Scientists at the Mechanical Engineering Laboratory are building mobile tele-existence systems. At NHK Science and Technology Research Laboratory, development and dissemination of very high definition television technologies are being aggressively pursued. At NTT Basic Research Laboratories, various image processing systems were demonstrated. The R&D activities at the Electrotechnical Laboratory include autonomous system software development and development of a three-wheeled pipe crawling inspection robot. The Advanced Telecommunications Research Laboratory has projects underway in intelligent communication, telephone interpretation, light- and radio-wave communication, and human vision and audition. At Fujitsu Systems Integration Laboratories, high-computational-speed parallel processors of interest to the telemanipulation subsystem are being developed. At Kyoto University the experimental work in visual perception was reviewed, and at the Kyoto Institute of Technology several image processing and computer graphics techniques were demonstrated. Researchers at Hitachi's Mechanical Engineering Research Laboratory presented information on real-time image processing for robot navigation and stair-traversing mobile robots. In general, although the presentations at the various facilities were interesting, no new information regarding their development efforts were revealed. The real benefit of the trip was finding that Japanese investigators are encountering the same problems in telemanipulation facing the R&D community as a whole.

INTRODUCTION

The purpose of this trip was to visit leading Japanese academic, industrial, and government scientists concerned with the development of advanced telerobotic systems and supporting technologies to observe firsthand the existing state-of-the-art of Japanese technologies in these areas and to discuss future plans for R&D with particular regard for what will be available in the 3-, 5-, and 7-year time frames.

SONY CORPORATION, ATSUGI R&D CENTER

Sony Corporation's R&D facility is in Atsugi, about 50 km south of central Tokyo. In addition to being an R&D center, the Atsugi facility is where Sony's broadcast-quality video equipment is manufactured. Most of Sony's R&D in new semiconductor technologies is conducted here, but because we were primarily interested in Sony's work on high-resolution color TV systems, we did not talk with the semiconductor developers. At present, Sony has about 30 scientists, engineers, and technicians working full-time on R&D of high-resolution TV systems, which are called HDVS (high definition video systems). This commitment of personnel to HDVS has been constant for the past 7 years. According to our hosts, Sony develops and markets its systems in 15-year cycles. So, over the course of the next 8 years they expect to make significant inroads into the video market with HDVS. The meetings at Atsugi were cordial and the general feeling was that Sony had "gone all out" to accommodate us and answer our questions. However, one couldn't help getting the impression that they were more intent on encouraging us to invest in existing systems than in telling us very much about what they expect to have available in 3, 5, or 7 years.

The HDVS system was demonstrated, and our consensus was that HDVS represents a dramatic improvement in picture quality over conventional National Television System Committee (NTSC) and Phase Alternation Line (PAL) systems in several important regards--detail resolution (1,200 TV lines/picture height); color fidelity (high saturation and brightness, lack of fringing); and image aspect ratio (16:9). During the HDVS demonstration, one of our hosts remarked that realism is enhanced by keeping the display screen flat, something Sony has done to the extent feasible with their displays. Sony has available for off-the-shelf purchase a complete line of HDVS broadcast-quality production equipment including a color camera; a black-and white camera; signal/image processing equipment (time base corrector, image enhancer, switcher, special effects generator); a 1-inch video tape recorder (VTR); a 120-inch projector display with auto-convergence; four color monitors (12, 18, 28, and 37 inches); and a 14-inch monochrome monitor. In addition, Sony has recently demonstrated working prototypes of an optical disk recorder, an HDVS fully digital VTR, and a converter from HDVS to NTSC/PAL. The currently available VTR provides only about 70 percent of the total video bandwidth of the HDVS standard (i.e., 28 MHz). In "2 to 3 years" Sony expects to make available the fully digital VTR, which will record 1,920 pixels per line for 1,045 active display lines. This will allow for recording/playback of the image quality currently available only with closed circuit operation.

Our greatest concerns were with the HDVS cameras. Obviously, many of the potential applications in which we are interested would benefit from compact, lightweight cameras. The camera head (minus lens) for the available color camera is 160 mm (W) by 354 mm (H) by 280 mm (D) (6.3 by 13.0 by 11 inches) and weighs about 10 kg (22 pounds). It is a 1-inch magnetic deflection Saticon three-tube system. We were very interested in what efforts were being undertaken to reduce size and weight possibly through the use of solid state sensors. Another serious limitation of currently available HDVS cameras is their relatively poor sensitivity and signal-to-noise (S/N) ratio characteristics. We came away from these meetings with the impression that Sony considers HDVS monitors and projection screen displays to be adequately developed and that Sony is concentrating a large proportion of its current efforts on the development of cameras and recorders, which might be available in 3 to 5 years.

At Sony Corporate Headquarters in Tokyo, several of Sony's latest consumer products were demonstrated, including digital audio cassette tape recorders, lightweight 8-mm camcorders packaged for underwater use, and the Budokkan chair. Next, we were guided through the Sony museum, where many "first of a kind" electronics items were on display. Following this, we were driven to Corporate HQ #2, where we toured "Media World," including demonstrations of large screen projection HDVS; teleconferencing equipment; office automation systems; man-machine interface (primarily information management systems); and new media systems (disk recorders/players, computer controlled video editing systems, mavica video recorders and printers). Though not particularly germane to our mission, this brief tour gave us firsthand experience of several innovative means for effectively managing and communicating information.

MECHANICAL ENGINEERING LABORATORY (MEL)

Dr. Tachi and his colleagues at MEL are building what Tachi calls mobile tele-existence systems. Dr. Tachi views the tele-existence approach (three-dimensional sensors, complex problem solving, supervisory control, realistic three-dimensional displays) as a logical and necessary next step toward the development of autonomous systems that will be able to cope effectively with the vagaries of unstructured environments. A great deal of Tachi's work on tele-existence systems has concentrated on the development of effective head-motion coupled (HMC) video systems. During our visit, we operated the same display unit that had been shown to Dan Hightower on his visit to MEL last year*. The display unit was tethered to a motorscooter-sized telerobot located in the parking lot just out back of Tachi's building. Each of us, in turn, remotely maneuvered the telerobot around an approximately 15- by 5-meter area in the parking lot. Operator head movements were measured mechanically for the horizontal rotational (i.e., pan) axis and were telemetered out to the vehicle. Control lags were noticeable, on the order of 100 milliseconds or so, but they were not felt to impose a serious limitation on vehicle maneuvering since the vehicle's speed was slow. Imagery provided the operator was in color but was of relatively poor resolution and color rendition and had a segmented or granular appearance due to the use of standard NTSC charge-coupled device (CCD) type sensors and color liquid crystal displays (LCD). Similar to the technique used with night vision goggles, the padding on the display consisted on foam rubber formed to fit the general dimensions of the face from forehead to the upper lip and covered with a soft, black, elastic material. The operator's head was held firmly against this facial padding by an easily adjusted velcro nape strap. On the remote vehicle, cameras were separated to a distance only slightly wider than normal interocular breadth and lenses were selected that provided a 1:1 match between the field of view of the cameras and the operator's field of view at the display (about 40° by 30° with 100-percent overlap). According to Dr. Tachi, accommodative demand of the system was fixed to a value of about 1.5 diopters, an average focus value for the human eye in its resting state. Convergence of the cameras was fixed at several meters in front of the cameras to a point thought to be at about the middle of the depth range scanned by the operator while operating the vehicle under normal conditions. Tachi stated that he had made a previous (presumably unpublished) attempt to match accommodative demand of the display to the vergence eye movements of the operator but had found vergence eye movements too difficult to measure accurately to effectively implement this control scheme.

*Hightower, J.D., and S. Kawano, "Recent developments at four Japanese facilities," Scientific Bulletin 11 (4), 82–90 (1986).

Another area of research activity for Dr. Tachi involves the development of prosthetic devices and other aids (i.e., mechanical guide dogs) for the handicapped and sensory impaired. Dr. Tachi has developed several mobile robot prototypes with the hope of replacing guide dogs for the blind. The mobile robots, referred to as MELDOG Mark 1, 2, 3, or 4, navigate using a navigational database or map and real-time inputs of relative bearing-range vectors for stationary or moving obstacles provided by ultrasonic transceiver arrays. To guide the user, Ag-AgCl wet electrodes are placed on the skin of each arm. Negative monophasic pulses of 100 microseconds duration are presented at 10 or 100 hertz to signal desired movement direction and if danger is present.

Dr. Tachi has performed psychophysical experiments that support Green's (1962) theory that perceived magnitudes of electrocutaneous stimulation are best described by pulse energy rather than pulse width or stimulation frequency alone. He has not yet developed any useful display systems that could be used to display tactile information to operators of telemanipulation systems.

Efforts have been made to develop an exoskeletal master controller for a dextrous multidigit end effector. However, the prototype measured angular displacements of only the first phalange of each finger. Distal linkages on the end effector's digit were directly coupled and closed at a constant angle; thus, if the proximal linkage moved 30° so did all distal links on the "finger." Although Dr. Tachi claims to have obtained good finger flexion/extension control, lateral positioning control was difficult because of the bulky controller and difficulties with coupling the controller to the subject's fingers (i.e., lateral movement of fingers resulted in torsion rather than lateral displacement of the exoskeletal finger links).

NHK SCIENCE AND TECHNOLOGY RESEARCH LABORATORY

Since NHK has been designated the lead laboratory for very high definition (VHD) television development in Japan, most of our brief meeting with them concerned VHD TV. In the words of one of our Sony hosts, NHK "defines the climate" within which all of the other development laboratories work. NHK refers to VHD TV under its own trademarked term Hi-Vision^{TM}. Development and dissemination of VHD technologies are being aggressively pursued at NHK. In 1990, Japanese direct broadcast satellite #3 (BS-3) is scheduled for launch from the Tanegashima Space Center. It will distribute VHD TV signals to Japan and its neighboring countries (presumably including the People's Republic of China). Initial use of the VHD channels will most likely be to small public theaters. A hand-held prototype VHD camera using 2/3-inch MS Saticon tube technology and weighing 8 kg (17.6 pounds) was built 2 years ago and demonstrated to us. To date, this is the most compact, lightest VHD camera to be successfully demonstrated in public. Mr. Mitsuhashi told us that the camera had been successfully encased for underwater use and had been used to collect underwater images from a depth of 10 meters (32 feet). He did not say, however, for whom this was done and why. Mitsuhashi said that Toshiba and NEC have major development efforts underway to provide solid state sensors for VHD cameras. NEC has had a functioning VHD CCD prototype in-house for about 1 year. Mitsuhashi speculated that within 2 to 3 years such equipment might be made generally available. In addition, work is ongoing at Matsushita (Panasonic), JVC, and Mitsubishi to provide a 1/2-inch VCR using MUSE-like techniques to compress the signal prior to recording. This kind of equipment might also be available in 2 to 3 years.

Mitsuhashi was also on-hand during the January 1987 tests of VHD TV in Washington, DC, in which the 28-MHz signal was compressed into 8.1 MHz (via NHK's MUSE technique) and broadcast over two consecutive UHF-TV frequency bands. He said that the only substantial problem encountered during this testing was multipath ghosting, made more noticeable by the high resolution of the imagery.

We also talked briefly with Shojiro Nagata, NHK's resident expert on image realism. He gave us five reprints (three in Japanese) covering his recent work in this area. According to Nagata, 30° horizontal field of view is a significant breakpoint in the function relating field of view (FOV) to perceived realism for video images. Conventional (i.e., NTSC/PAL) video is intended to be viewed with a 10° FOV. VHD TV was designed to match the normal human eye's resolving capability while providing the 30° FOV. Nagata also stated that as the width of the display is increased up to and beyond 30°, the effectiveness of stereoscopic cues for accurate perception of spatial relationships in the depicted scene diminishes, while the effectiveness of motion parallax cues increases. Nagata also said that maintaining the high frequency components (i.e., high resolution for details) in the peripheral regions of the display is critical to maintaining the effectiveness of the motion parallax cues. Unfortunately, none of the papers that Nagata presented us directly substantiate these claims.

The discussions at NHK Laboratory were less cordial and open than we had wanted them to be. The feeling among our group was that we were treated politely and with respect, but that we were also for the most part confined to a conference room and shown very little of their current R&D efforts.

NTT BASIC RESEARCH LABORATORIES

At NTT we were hosted by the Information Science Department (ISD) at the Musashino Research Center. ISD consists of three branches: (1) Computer Science--concerned with AI topics, parallel computing architectures and software environments, and speech understanding; (2) Human Science--concerned with human and machine vision, advanced graphics, human cognition, and speech intelligibility; and (3) Computervision (CV) Communication Systems--concerned with networking strategies, fiber optic datalinks, and fundamentals of signal transmission. Our discussions were limited to the work of the Computer Science and Human Science Branches. We were shown an image understanding system which, when fed a digitized image of a typical office hallway, could segment objects and accurately calculated their range, bearing, and size by exploiting perspective information derivable from converging lines in the images. The entire computational process required several minutes to complete, but it was run on only an ordinary PC-type machine. Our next visit was to the laboratory of Dr. Toshiaka Imada, who has been developing an AI/image processing/graphics workstation that will provide comparable capability to a Symbolics machine at about one-third the cost. The workstation uses a 68101 microprocessor. An interpreter has been developed for the machine that allows coding of multiple languages (e.g., Lisp, Prolog, FORTRAN) within the same program. Imada said that the system will be available in the summer of 1987.

In the area of computer graphics, prototype hardware that is being developed and optimized for real-time calculation of ray-tracing algorithms and fractals was demonstrated.

Finally, we were briefed on recent work with pulsed-radar holography that has been applied to the recurring utility company problem of detecting the presence and position of conduits buried underground. While this work is not directly pertinent to our immediate interests, it does involve interesting signal- and information-processing techniques, and similar techniques may prove very useful for the detection and identification of objects buried under the floor of the ocean.

MINISTRY OF INTERNATIONAL TRADE AND INDUSTRY (MITI) ELECTROTECHNICAL LABORATORY (ETL)

Dr. Okada discussed research and development activities that are ongoing at ETL and other research facilities. According to Dr. Okada, MITI's teleoperator development program has funded:

- development of master controllers at MEL
- dextrous end effector development at Mitsubishi
- autonomous system software development at ETL

He then gave us a tour through his telerobotics laboratory. At present ETL is finishing development of a three-wheeled pipe crawling inspection robot referred to as MOGRER. MOGRER consists of two hinged-arms in a scissors structure. Wheels at the end of the arms are held in contact with the walls of pipes via spring-bound level action of the hinged arms, which permit adjustments to variations/transitions in pipe diameters.

Another ongoing project has produced a stereo video image upon which a wire-frame model of the manipulator's geometry is overlaid. Instructions sent to the manipulator, and sensor information received from the slave, are used to make adjustments in the wire-frame model to coincide with changes in manipulator position and orientation. Operators view the images using goggles possessing LCD shutters alternating at 10 hertz in concert with maximum cathode ray tube (CRT) image update rates. It was clear that his approach could be very useful to telemanipulation when visibility is limited because the manipulator is obscured by objects or lighting and turbidity levels are less than ideal.

ADVANCED TELECOMMUNICATIONS RESEARCH (ATR) LABORATORY

ATR Laboratory is in Osaka. Our host, Dr. Takao Sato, explained that ATR is a new type of organization within the Japanese research establishment--a laboratory that has been granted a charter to exist only 7 years. ATR has been in existence for only 1 year, but major research efforts are already underway in four areas: (1) intelligent communications, (2) telephone interpretation, (3) light- and radio-wave communications, and (4) human vision and audition. Dr. Sato's group is the latter. In general, the work of his group of about 20 researchers is directed toward basic research to support development of information processing and communication systems that are suited to efficient use by human operators. Efforts are ongoing in mathematical modeling of perceptual and recognition processes in human vision and audition, as well as in human cognition. Development efforts are underway to advance the technologies available for reliable recognition of ideographic characters, arbitrary symbols, visual images, and human speech. More fundamentally, the goal of Sato's group is a clear definition of the optimal form that the human/machine interface should take in our increasingly information-loaded environment.

In particular, efforts are underway to implement Dr. Kushima's (of Tokyo University) neo-cognitron model of visual recognition. Dr. Inui of Kyoto University is just now commencing this work on an N-Cube machine, a very fast 256 parallel processor machine using a UNIX-like operating environment. In addition, the laboratory is equipped with a truly impressive array of fast image processing machines such as Symbolics 3670s, 3675s; a LucasFilm PIXAR machine; and several VAX minis. Dr. Ogata is implementing the NASA/Ames Watson/Ahumada model of visual motion on the Symbolics machines. Dr. Sato uses a MASSCOMP to generate random dot cinematograms for a series of studies on the effects of luminance and color contrast on visual motion detection. Other researchers at ATR are using structured light to determine the three-dimensional shapes of complex objects. At present, this work involves use of static images, but once the appropriate algorithms are worked out for these, implementation of real-time capability will simply be a matter of an equipment upgrade.

At ATR, we were impressed with the amount of investment in facilities and equipment that the Japanese have made in such a short span of time and the amount of research talent that has been assembled to study fundamental human perceptual and cognitive processes. Within a single year ATR has become one of the leading research laboratories in Japan. If work progresses as planned, ATR will undoubtedly emerge as one the world's leading research organizations within the coming years.

FUJITSU SYSTEMS INTEGRATION LABORATORIES

Presentations by Fujitsu engineers and scientists were made covering several areas concerned with computer-aided design (CAD) approaches to industrial robot programming, image and parallel processing techniques designed to quickly generate polyhedrons for CAD systems, and sensing systems such as phased array radar and forward looking infrared (FLIR) scanner.

No work was ongoing in areas of interest to the telemanipulation subsystem save the advantages offered by high computational speeds of parallel processors.

KYOTO UNIVERSITY (KU)

At Kyoto University, we reviewed the experimental work of two doctoral candidates in visual perception. Mr. Shin-Ya Nishida presented his work involving inhibition between spatial orientation channels in the human eye. Mr. Hiroshi Ando's work involves textural discrimination with various random dot patterns and could be applied to the development of algorithms for machine vision. While at KU we were also given a tour of the KU Computing Center, where Dr. Nakamura is conducting research on various image processing techniques and natural language understanding techniques. Working on a pair of Symbolics 3800 machines, Dr. Nakamura is working on systems that can segment images and determine the spatial relationships of objects in "Blocks World"-type scenes. We were also shown a variety of computer equipment for image processing tasks too numerous to mention here. The heart of the KU Computer Center is, however, worthy of note--a FACOM (Fujitsu) VP-200 that is due to be upgraded to a VP-400 next year. The present system performs vectorized calculations on photonic processors and is capable of processing rates in excess of 500 million instructions per second (MIPS).

KYOTO INSTITUTE OF TECHNOLOGY (KIT)

In the laboratory of Drs. Fukushima and Niimi at KIT we were given a lengthy demonstration of several image processing and computer graphics techniques, all of which were fairly commonplace by current standards. We were also given laboratory demonstrations by several graduate-level students of Dr. Akita. Shimizu and Eriko Miyahara demonstrated their apparatus and testing procedures for a series of studies of rod-cone interactions at mesopic luminance levels. Other students of Dr. Akita showed us their recent work on color and motion aftereffects.

HITACHI LTD., MECHANICAL ENGINEERING RESEARCH LABORATORY (MERL)

The meeting was focused upon real-time image processing for robot navigation and stairway-traversing mobile robots. Mr. Kamejima and his colleagues have been developing a recursive procedure, using a two-dimensional diffusion algorithm, a maximum likelihood approach, as well as two-dimensional context sensitive grammar, to enable extraction of structural information from random image fields. The procedure is sufficiently fast, and its decision hierarchy sufficiently small, that real-time navigation about obstacles can be performed by a slow-moving mobile robot.

Mr. Iwamoto described the capabilities of MERL's advanced mobility robots. The majority of the discussion concentrated upon the stairway-traversing robot. The robot is essentially a track-driven crawler that uses a third planetary wheel to alter the track's angle of attack of obstacles and to increase the track's contact area (length) with the ground when additional traction is required (e.g., when crawling up stairs). Proximity sensors are used in front, behind, and underneath the robot to detect distances from obstacles and the floor. Proximity and video image analysis information is used jointly to permit autonomous navigation and control of track geometry to permit obstacle encounter and traversal.

Although Hitachi is a leading developer of robotic end effectors (e.g., Hitachi's shaped memory alloy (SMA) hand), discussions of end effectors were severely limited by Hitachi. We did discover that the SMA hand was still unable to produce a grasp force of more than 2 to 3 newtons and that Hitachi was relying completely upon computer control of the hand; MEL's master controller would be used if needed in the future.

CONCLUDING REMARKS

Although the industrial/government funded laboratories that had developed reputations for research and development in telemanipulation subsystems (e.g., MEL and Hitachi Ltd.) provided no new information regarding their development efforts and were obviously unwilling to discuss their current efforts even in vague terms, the real benefit of the trip was finding that Japanese investigators were encountering the same problems in telemanipulation facing the research and development community as a whole. Our meetings may make future cooperation and communication between ourselves and the Japanese investigators visited less difficult, particularly if they are allowed to accept our invitations to visit our laboratories.

Donald K. Moore received a degree in electrical engineering from Texas A&M University in 1954. Mr. Moore is head of the Advanced Systems Division and assistant technical director for the Naval Ocean Systems Center, Hawaii Laboratory. He is responsible for the management of technical programs that include the research and development of remotely manned systems; optical fiber datalinks; semisubmersible ships; other ocean engineering activities; and research in cognitive sciences, human factors issues, and man-machine interfaces. During the 1970s, he participated in the United States/Japan Natural Resource exchange program, Marine Facilities Panel, attending working meetings in both countries. He has been associated with the development and operation of manned, free-swimming submersibles; unmanned, tethered submersibles; remotely manned, telepresence systems; underwater acoustic instrumentation; rocket- and satellite-borne electro-optical instrumentation; and inertial navigation systems.

MARINE SCIENCE IN BOMBAY

Wayne V. Burt

The Bombay Center of the National Institute of Oceanography is engaged in many activities related to marine pollution and its impact on the environment. These activities include performing environmental impact studies for industry and government agencies and studying the rate of deposition of heavy metals and other pollutants and the effects of these pollutants on the flora and fauna.

The National Institute of Oceanography (NIO) has its headquarters in Goa, with regional centers in Bombay and Cochin on the west coast of India and at Waltair on the east coast of India.

The regional center at Bombay is responsible for coastal studies extending from about 80 km south of Bombay northward to the Indian border with Pakistan. Its three divisions, Physical, Biological, and Chemical Oceanography, carry out research in nearshore waters, bays, and estuaries. It has no vessels of its own and normally charters small craft for nearshore studies of currents and sampling biota and water.

European contact with the area known as Bombay dates back to very early in the 16th century when the Portuguese first landed there and set up a trading post. Its name is derived from either the Portuguese words Bom and Bahia, i.e., Good Bay, or Mumba Bai, a Hindu goddess. The Sultan of Gujarat ceded Bombay to the Portuguese in 1534; in 1661 the Portuguese gave it to Charles II of England as part of the dowry of Catherine of Braganza, sister of the King of Portugal. From 1661 until 1947 it was under British control.

Bombay is the financial center and richest city in India. Its citizens, who make up only 1 percent of the population of the country, pay 40 percent of the income tax that is paid in all of India. It is the largest port in terms of the tonnage shipped in and out of its harbor. It is a major center for manufacturing textiles, as well as engineering and electronics equipment. The city is long and narrow. Its major transportation problems are solved by high speed electric trains that move 3,000,000 people a day in and out of the center of the city. This number of people is more than three-fourths as many people as ride all of the subways in New York City and environs.

Greater Bombay has a total area of only 184 mi^2 with a population approaching 9,000,000. Therefore, it is one of the most crowded cities in the world, with about 50,000 people per square mile. Skyscraper apartment buildings are taking over much of the city, giving it a Manhattan-like skyline. Originally the city consisted of one large island and six smaller ones. Much of the waterway area between the islands has been filled in to make more room for the burgeoning population.

For many years much of the sewage from the industries and the inhabitants was dumped into the sea, creeks, bays, and estuarine waterways around the original islands, polluting the marine and estuarine habitat.

The regional center of NIO is engaged in many activities related to marine pollution and its impact on the environment. A major portion of its financial support is from sponsored research. Environmental impact studies are required before any industrial development is allowed. These studies are made by the NIO regional laboratory and are paid for by the industry involved or by concerned governmental sponsoring agencies. With only 8 scientists and 12 supporting staff, this places a heavy burden on the laboratory.

The young Scientist-in-Charge of the laboratory, Dr. M.D. Zingde, first discussed with me an environmental impact study that laboratory was making in the Gulf of Kutch about 180 km southeast of the Pakistan border. The Indian Central Electricity Authority is preparing a feasibility study for the construction of a tidal barrage there for generating electricity. The tides in the inner reaches of the Gulf of Kutch range from 6 to 8 meters. There is a relatively narrow bottleneck near the upper end of the gulf with a shallow sill where a barrage could be placed and give an average head of 3 meters for generating power. The area around the gulf is a desert that now has very few inhabitants. However, some of the marshy areas on the edges of the gulf are inhabited by some rare species of birds and animals. This brings the environmentalists into the picture.

There is also a relatively large industry where salt is being made from seawater in a series of salt ponds. The earth under the salt ponds has a salinity of 120 ppt. The Central Salt and Marine Chemical Research Institute is studying the likely impact of the proposed tidal barrage on the efficiency of the salt production in the ponds.

In addition, despite the lack of people living around the gulf, there is already some pollution there. This pollution comes from a large plant that is manufacturing soda ash from limestone and seawater. The desert area around the gulf has not been very productive for agriculture. However, during the past few years, the northern limit of the heavy summer monsoon rains appears to have moved northward, from a little north of Bombay to the Gulf of Kutch region, giving the area a surplus of rain and increasing the potential for agriculture in the area.

Obtaining enough potable water to supply the city of Bombay is a problem because most of the rainfall comes in the 3 to 4 months of the summer southwest monsoon. Most of the water comes from reservoirs behind dams on rivers that flow down to the coast and some of it from as far inland as 100 km. The city also has several large reservoirs to store water for use when the rivers are almost dry. One of these is on the top of a large hill in the center of the city. For a number of years it had one of the strangest pollution problems of any reservoir that I know of. The city has a small percentage of Parsees who originally came from Persia to escape Moslem persecution, and many are now wealthy businessmen. They have half a dozen tall towers (called towers of silence) where they place their dead and let the vultures eat them. The bones are piled in the bottom of the tower where they eventually weather away. These towers are in a grove of trees right next to the big reservoir. In the past the vultures would fly over the reservoir and drop bones and meat into the reservoir and pollute its waters. Finally a wealthy Parsee put up the money to cover the reservoir and plant a most beautiful garden park on top of the cover. It is called the Hanging Gardens and is one of the most beautiful and most used parks in the city.

Until a few decades ago, much of the industrial waste and sewage was untreated and flowed into the sea and the bays and inlets between the islands through many outlets. Presently the city is constructing a number of trunk sewer pipes to collect the sewage. It will be given primary treatment and then will flow out into the ocean through three massive outlets. One of these outlets was under construction near the hotel where I stayed. It was a huge square poured concrete conduit, large enough to drive a truck through. It will be built out under the seafloor for a distance of about 1 mile from shore. During most of the year there is a slow southward drift along the shore, superimposed on a north-south oscillating tidal current. Only during the summer monsoon months is there some onshore drift. The effects of its tendency to bring the effluent onto the shore are partially ameliorated by dilution from the heavy runoff due to the monsoon rains.

The NIO laboratory is studying the rate of deposition of heavy metals and other pollutants in the bottom sediments of the main harbor, which is downstream from the area where much of the heavy industry has been discharging pollutants for years. The researchers are able to date the sediments and determine the rate at which each pollutant settles to the bottom. Examination of cores that contain sediments laid down during the past 60 years indicates that the rate of deposition of each of the heavy metals has stayed almost constant during that period of time. On the other hand, the rate of deposition of hydrocarbons in the sediments has increased constantly and rapidly over the past 60 years. Usually hydrocarbons found on the bottom of harbors come from oil spills from ships. Each type of oil has a characteristic spectrum when subjected to infrared spectroptic analysis. Used crankcase oil is one of the hydrocarbons found in the sediments.

A good deal of effort is going into studying the effects of the various pollutants in the water on the flora and fauna. In the polluted areas, there are very few species present. Present studies indicate that, in general, there is a higher productivity in the lower trophic levels in the polluted areas than in the unpolluted areas. This is not true of the higher trophic levels, which have lower productivity than normal in the polluted areas. Therefore, the polluted regions are classified as special ecosystems where the transfer coefficient from one trophic level to the level above may be far less than the normally assumed conversion factor of 10 percent.

Dyes, floats, and current meters are being used to determine the current structure along the coast and in the bays and inlets around and in Bombay. About 50 Aanderaa and Aanderaa clone current meters are available from NIO Goa and NIO Bombay. Current data are being used by researchers at NIO Goa to construct models of the currents in the area around Bombay.

The laboratory has some of the very latest foreign-made spectrophotometric instruments to determine the components of the pollutants in water, sediment, and plant and animal samples.

I could not help but note the high degree of esprit de corps of the staff, who were relatively young and were eager to explain their work to me.

The address of the laboratory is Sea Shell, Seven Bungalows, Versova, Bombay. Originally there were seven lovely homes out on a point about 100 meters from the road and another 100 meters down to a sea cliff, giving spacious views of the ocean and coastline. Now the area is thickly covered with very high rise apartments that block out all the views from the bungalows. The same thing has happened in what used to be the best seashore residential areas.

PERMANENT MAGNETS IN JAPAN AND THE 1987 TOKYO INTERMAG CONFERENCE

K.J. Strnat

At the International Magnetics Conference, a variety of topics covering all aspects of magnetism and magnetic materials was presented. This article reviews highlights of that conference. In the magnetic recording area, recent developments in perpendicular recording technology and the media for it are described. In the field of magneto-optics, information is presented on magneto-optic disk systems for digital audio recording and digital data file memories. Under the broad topic of permanent magnets, rare-earth permanent magnets of Nd-Fe-B and Sm-Co-Fe alloys, ternary and quaternary rare-earth/transition-metal compounds, and other hard magnetic materials are discussed. Observations from visits to the Society for Non-Traditional Technology, Mitsubishi Steel Manufacturing Company, Hitachi Metals Company, Shin-Etsu Chemical Company, Sumitomo Special Metals Company, Toshiba Research and Development Center, Tohoku University, MG Company, and Seiko-Epson Corporation are presented.

INTRODUCTION

This is a report on experiences and observations made during a 3-week trip to Japan in April 1987. The main occasion for this trip was the International Conference on Magnetics, INTERMAG, held in Tokyo from 14 through 17 April. In the 2 weeks preceding the conference, Dr. Herbert Leupold, of the U.S. Army Electronics Technology and Devices (ET&D) Laboratory, Ft. Monmouth, NJ, and I visited a number of companies that are producers of rare-earth permanent magnets (REPM) and a research group working in the same field at Tohoku University in Sendai. In several of the places visited, we also lectured on the recent work in our respective laboratories in the field of permanent magnets and their device applications. We established contacts with many Japanese research scientists, development engineers, and technical managers active in this field in which Dr. Leupold's organization and the U.S. Army Research Office (ARO) have long conducted and sponsored materials research and device development. For myself, the trip was a welcome opportunity to update my knowledge of the Japanese magnetic materials scene and to renew many longstanding personal contacts. We were made to feel very welcome at all places we visited, had a fruitful exchange of information and ideas, and I can most highly praise the outstanding hospitality afforded us everywhere.

INTERNATIONAL MAGNETICS CONFERENCE

This INTERMAG Conference was the 25th in a series of large annual conferences that are principally organized by the Magnetics Society of the Institute of Electrical and Electronic Engineers (IEEE). These meetings cover all aspects of magnetism, useful magnetic materials, their applications in many areas of technology, measuring instruments, and the design and production of devices and machines based on magnetics, including their economics. Traditionally, this conference emphasizes applications and materials with clearly discernible device uses over basic magnetic science and theory, although the latter are also represented at INTERMAG.* The conference began as a domestic American meeting but soon adopted its present 3-year operating cycle: it is now held in the United States twice in a row and each third year in another industrialized country that has a strong tradition of work in the field of magnetics.

This year's conference was cosponsored by the Magnetics Society of Japan, which did an exemplary job of organizing the technical meetings, providing services to participants, and generally offering wonderful hospitality. The meeting was the largest INTERMAG ever in terms of the number of participants (about 1,700), the number of technical papers (about 680), and the variety of topics covered. Taking advantage of the fact that so many foreign magneticians were in the country, other Japanese organizations arranged three related international symposia immediately preceding or following INTERMAG, covering physics of magnetic materials, magnetism of intermetallic compounds, and magneto-optics. At the INTERMAG site, the Keio Plaza Hotel in Shinjuku, there was also an all-day tutorial on magnetic recording, on Monday before the conference. One disadvantage of such a large conference with a broad topical coverage is, of course, that many parallel sessions must be held, and so it is difficult to hear anything outside one's immediate field of interest. There were always seven or eight simultaneous sessions. My field—hard magnetic materials and their applications (permanent magnets)—was particularly active at this conference, with seven long sessions preempting, for me, other topics of potential interest during seven of the eight available half-day session periods. Thus, the following discussion will concentrate heavily on news in the permanent magnet field. However, I shall also attempt an overview of other specialties, based mostly on abstracts and conversations with speakers, and will in fact begin with that.

Magnetic Recording

If we judge the importance of a subfield of magnetics by the number of sessions and papers devoted to it at this conference, then the first place clearly belonged to magnetic recording media, recording methods, and the underlying physical theory. Because of the size of the market for magnetic recording products, this complex of topics has been in the foreground for many years. There was heavy emphasis on perpendicular recording technology and the media for it. In conventional recording, the magnetized "bits" lie in the plane of the medium, while in perpendicular recording the magnetization is through the thickness of the tape or disk. This new technique is said to allow a higher data density to be recorded on tapes or disks, and it will probably replace the long-established method of longitudinal recording in many applications. The preferred medium for perpendicular recording is a sputter-deposited film of a Co-Cr or Fe-Cr alloy. The concept is over 10 years old, but now the Co-Cr medium appears to be reaching production maturity. Considering magnetic recording media in general: as higher recording densities demand higher remanence and coercive force values, there is a definite trend away from the traditional oxide media and toward metallic thin films, which can provide this combination. Papers at this conference dealt with a variety of alloy compositions, deposition methods, and the mechanisms by which the desired perpendicular anisotropy and

*Papers presented at the 1987 INTERMAG Conference will be published in the September 1987 issue of the *IEEE Transactions on Magnetics*, IEEE, New York.

coercivities in the range of 200 to 2,000 Oe can be obtained. This is analogous to development trends in permanent magnets where all recent additions to the arsenal of hard magnetic materials have also been metallic alloys.

Magneto-Optics

The second topic in terms of the number of papers was magneto-optics. The so-called magneto-optic recording technology is now reaching the commercial pilot stage, with the introduction of disk systems for digital audio recording and digital data file memories being scheduled for later this year by several Japanese companies. The various contributing components of this technology have been under investigation and development for about 25 years now. This includes thermomagnetic recording and magneto-optic readout of the recorded information. Essential prerequisites for the systems now being introduced or under development were the amorphous rare-earth/transition-metal alloy films, which combine high saturation and fairly high coercivity with a large Kerr rotation, and laser-based optical systems with electro-optical modulation for both recording and reading. The systems now available use disk-shaped recording media with sputtered films of Tb(Gd)-Fe(Co) alloys with overlayers that may have two functions: to protect the magnetic film and to enhance the Kerr rotation by interference effects (ZnSe and $Tb-SiO_2$ doped with up to 80 percent Tb are used for this). In some cases ferromagnetic underlayers (e.g., NiFe) are used to increase the recording sensitivity and bit stability. Compared with conventional magnetic recording, these magneto-optic disks promise higher data density and therefore large-capacity recording systems; compared with the nonmagnetic thermal-optical technology used in present compact-disk (CD) audio recording, the magneto-optic schemes allow erasing and rewriting. However, there appear to be unsolved problems and, thus, a need for development work with regard to all these advantageous features of magneto-optic recording to make the new technology truly competitive. The bit density must be further enhanced by improving the magnetic recording media and the recording method. Direct overwriting as is used in present magnetic tape recorders is highly desirable, but at present there remains too much of the prerecorded signal on the disks, requiring a separate erasing step; generally, higher data transfer rates and very low access times are needed to make magneto-optic memories useful for digital video recording and more competitive as a mass storage medium for computer memories. Investigations with these improvements as their objectives were reported at this INTERMAG. They include combinations of conventional, purely magnetic recording with magneto-optic readout schemes; different multilayer recording disk designs; thermal magnetic recording with modulation of the magnetic field instead of the laser light; and other novel concepts. The thermo-magnetic recording/magneto-optic readout schemes generally use perpendicular recording; thus, they require the existence of a strong uniaxial magnetic anisotropy with the easy direction perpendicular to the plane of the film. While this anisotropy can be produced by appropriate sputtering conditions, its physical origin is still uncertain. Several papers were devoted to this basic topic.

Permanent Magnets (PM)

The topic "Hard Magnetic Materials" commanded the third largest body of papers, with 7 sessions and 65 papers, rivaling magneto-optics. This was about 10 percent of the total number of papers in the conference. Fifty-six of these papers were devoted to rare-earth permanent magnets (REPM). This was the strongest showing that permanent magnets have made at any of the annual INTERMAG or Magnetism and Magnetic Materials conferences. The dominant subtopic was again, as in the last 3 years, the new subgroup of REPM materials based on rare-earth-iron-boron compounds of the 2-14-1 stoichiometry. The prototype material of this family, Nd-Fe-B, and two alternative ways of producing permanent magnets from it had been announced in 1983. At this conference, over 40 of the papers were devoted to various aspects of Nd-Fe-B and a number of derivatives that have been developed since then. Alloy modifications; microstructures; the physical origins of the high coercivity; the magneto-crystalline anisotropy underlying it; production methods for sintered, rapidly quenched, and bonded magnets; properties of magnets over a wide temperature range; device applications; and engineering design methods were all covered in these seven sessions. Additional papers on device uses of permanent magnets were scattered through other sessions as well, including magnetic levitation and linear-motor propulsion of tracked vehicles and permanent magnet motor and position-sensor applications. Regarding the Nd-Fe-B magnets, many of the papers were concerned with the phenomena that limit their applications at elevated temperatures above about 150 °C (the rapid decline of coercivity on heating and the propensity of Nd-Fe for rapid corrosion) as well as at cryogenic temperatures (problems related to the spin reorientation on cooling). Many research groups are trying to improve the elevated temperature stability of Nd-Fe-B by alloying measures designed to increase the Curie temperature (Co additions) or the coercivity (Dy, Al, Nb, Ga, etc.). Attempts to use RE-Fe-B based materials in polymer-bonded matrix magnets have also met with severe obstacles (R or RE = rare earth).

Several groups are now attempting to learn how to make powders of such alloys, cast or presintered, without destroying the coercive force during grinding or to restore and preserve it after comminution by heat treating and surface coating. So far, most results are discouraging, and one is forced to rely on rapidly quenched, isotropic powders for bonded magnets.

Another group of papers was concerned with the relationship between microstructure and coercivity in the so-called 2-17 magnets based on Sm-Co-Fe alloys. Of all the REPM, these are by far the best for elevated temperature applications--some being useful up to about 350 °C--and they are also much more suitable for use in high-energy bonded magnets.

A few papers reported on the search for new candidate magnet materials among ternary or quaternary compounds involving rare earths and transition metals. K. Ohashi et al. prepared the ternary phases $RTiFe_{10}$ with R = Ce, Pr, Nd, and Sm as stable compounds. The samarium compound is reported to have a high uniaxial anisotropy, making it suitable for permanent magnets. (This work was based on earlier reports by F.J. Cadieu et al. of high-coercivity Sm-Ti-Fe films made by sputtering.) However, these compounds have Curie temperatures somewhat below those of the corresponding $R_2Fe_{14}B$ compounds, and the rare-earth partner must again be the fairly rare element Sm rather than the more plentiful Nd, so these compounds do not seem to offer a practical advantage over those already in use for REPM. S. Higano et al. studied the magnetic properties of nitrided rare-earth/transition-metal intermetallics, finding a significant increase of the saturation magnetization for Sm_2Fe_{17}-N at moderate nitrogen contents. But again, it does not appear that these are practical new PM candidate materials. Studies of the magnetism of $R_2Co_{14}B$ compounds with individual light and heavy rare earths, as well as with RE mixtures, revealed interesting information about their basic magnetism and spin reorientation phenomena. They showed $Pr_2Co_{14}B$ to have a very high crystal anisotropy at room temperature; but again, no candidates for practical new magnet materials were reported. I emphasize this line of research because there undoubtedly exist many ferro- and ferri-magnetic ternary and quaternary intermetallic compounds of ferro-magnetic transition metals with rare-earth partners, and some of these may indeed have the potential of yet higher energy products and better permanent magnet properties than the best now available.

There were five invited papers in the hard magnetic materials sessions. I reviewed the 20-year development history and future prospects of the rare-earth magnets. J. Livingston summarized the efforts to understand the physical origins of high coercive force; he clearly exposed the conceptual and experimental difficulties in distinguishing domain nucleation from local wall pinning. G. Asti surveyed the complicated topic of the magneto-crystalline anisotropy in rare-earth alloys, the most important basic property controlling coercivity. Zhang Xi gave a detailed report on the efforts to develop a Nd-Fe-B production technology in China. He emphasized the very large RE raw material base that exists in the People's Republic of China. S. Jin and G.Y. Chin reviewed the development state of Fe-Cr-Co, a family of ductile magnet alloys that competes directly with the older Alnicos.

Plenary Session

The session chairman, Prof. S. Uchiyama, first acknowledged the outstanding work of the Japanese organizing committee, chaired by Prof. S. Iwasaki of Tohoku University, and of the U.S. management committee chaired by Prof. M.H. Kryder of Carnegie-Mellon University. He then introduced the main speaker of the evening, Dr. Saburo Okita, who gave a general interest address titled "Japan in the World Economy and Technology." This was an excellent choice of both speaker and topic, particularly in view of the recent difficulties in international trade between Japan and the United States. After reflecting on his lifetime of service, including World War II and the postwar periods of reconstruction and subsequent economic expansion, Dr. Okita made very poignant observations concerning the nature and roots of the present international trade friction. His thoughtful comments and recommendations for future action left me convinced that if Dr. Okita is representative, Japanese economic planning is conducted by very reasonable and responsible people. Dr. Okita has an educational background as an electrical engineer who later earned a Ph.D. in economics, and his 30-year governmental career included positions as Director of the Economic Planning Agency and Minister of Foreign Affairs. In the last 20 years, he headed the private Japan Economic Research Center; served on committees of the United Nations, OECD, and the World Bank; and is now chairman of the Institute for Domestic and International Policy Studies as well as president of the International University of Japan. The INTERMAG organizers could hardly have made a better choice for their plenary speaker!

Industrial Exhibition

There was also a large and well organized exhibition of magnetic products, measuring instruments, and information featuring 45 booths, with most of the exhibitors being Japanese companies. A very informative highlight of this exhibition was a display on magnetic recording set up by the Japan Society for the Promotion of Science (JSPS). The display commemorated a 10-year activity by the JSPS Committee 144 to develop and promote the new high-density magnetic recording technology, perpendicular recording. This exhibit highlights the way in which Japanese industry promotes cooperative research and development (R&D) and educational activities, a method that obviously pays off handsomely in fast technological development and eventual economic success.

VISITS TO COMPANIES AND INSTITUTES

Society for Non-Traditional Technology

The Society for Non-Traditional Technology is in Toranomon, Minato-ku, Tokyo. This organization promotes the exchange of technical information and the development of new products in emerging technological fields. It also seems to engage in international negotiations regarding materials resources, technology transfer, etc. It is about 10 years old now, supported in part by Japanese government agencies and in part by many industrial companies on a membership basis. The society has for some time also operated laboratories for novel machining, processing, and testing techniques; it seems that this part of the society's operation is being phased out again. Other activities include organizing technical lectures for a broad audience drawn from member companies and arranging specialized conferences.

Dr. Leupold and I spoke before an audience of about 50 scientists and engineers, reviewing recent developments in permanent magnet materials, the spectrum of REPM materials and properties now available, matching of materials to certain application requirements, and principles of device design with emphasis on some unique new magnetic device concepts possible only with rare-earth magnets. Prof. Hirohisa Uchida of Tokai University was our expert interpreter. Much of the discussion following the talks centered on polymer-matrix magnets, for which there is rapidly growing interest among magnet users and manufacturers. Such magnets, based on Sm-Co, have been in moderately large scale production by several Japanese companies, with others appearing ready to enter the market. All these manufacturers are trying to come up with a viable new matrix product based on Nd-Fe-B.

During a dinner meeting hosted by the society, represented by Prof. Kaneko and Mr. Kurino, we met several people who are active in this matrix magnet area, namely, Dr. Masaaki Hamano, who is board director and manager of R&D of the MG Company, Ltd., a polymer processing firm that has an extensive line of injection-molded magnet products; Norihiko Tanabe, the president of Tanabe Kogyo Co., Ltd. of Yokohama, which makes magnetic field injection molding machines for the manufacture of plastic-bonded magnets; and Isao Iwai, representative director of DJK International Inc., an independent Tokyo testing and consulting firm active in the same field.

With Prof. Kaneko and Mr. Kurino we also had preliminary discussions concerning their plan to hold the 10th International Workshop on Rare-Earth Permanent Magnets and their Applications in Japan, probably in the summer of 1989. The society had organized one of these specialized 4-day conferences once before, the fourth workshop, which was held at Hakone National Park in 1979.

Mitsubishi Steel Manufacturing Company

The Mitsubishi Steel Manufacturing Company (MSMC) is a traditional manufacturer of many kinds of permanent magnets. It added REPM to its product line early on, in the 1970s, initially sintered $SmCo_5$ and later polymer-bonded versions. Much of the research is still done at the central R&D laboratories of MSMC, where we visited. But there are now two separate production firms for magnets in the Mitsubishi family: the Mitsubishi Steel Magnetics Company, which produces sintered Sm-Co and bonded ferrites, and the Dia-Rare Earth Magnetics Co., a joint venture of MSMC and Mitsubishi Chemical Co., specializing in bonded REPM production. Our principal host was Dr. Kimiyuki Kamino, who is research manager at MSMC and a director of the two new production companies. We also met Tadahiro Ishikawa, director of the Mitsubishi Steel Magnetics Company; Sakae Higano, a senior research engineer; and several more of Dr. Kamino's co-workers. We were shown some of the laboratories, which are relatively old but well equipped for physical and chemical analysis and for magnetic measurements on hard and soft magnetic materials. Magnetic instruments range from a TOEI vibrating sample magnetometer for basic magnetic property measurements, through loop tracers used in magnet development work, to some specialized, production-related test equipment. One very impressive demonstration involved a desk-top computer programmed for two-dimensional magnetic circuit analysis by the finite element technique. It is capable of mapping magnetic flux distribution and equipotential lines in unconventional ways that make interpretation easy. As an example, we were shown steps in analyzing the design of a flat head actuator for a computer disk drive. It appears that the company is well equipped to assist magnet customers in optimizing their designs.

With regard to REPM, we heard that Mitsubishi has a fairly large scale commercial production of magnetic components using polymer-bonded Sm-Co (2-17) and Nd-Fe-B magnet material. The main products are a stator for a coreless linear actuator that is part of a compact disc head drive produced by Mitsubishi Electric Company and uses Sm-Co as the magnetic component and a 10-pole rotor for a stepping motor that drives a floppy disk head and uses Nd-Fe. We were also shown a focusing magnet for the electron beam in the cathode ray tube (CRT) of a video cassette recorder (VCR) camera, which is a bonded Sm-Co magnet. Surprisingly, the magnet alloys used are purchased from other companies, with the 2-17 now apparently coming from the Japanese Santoku Company, while the Nd-Fe-B material is Magnequench powder imported from the General Motors Corporation, Delco-Remy Division, in Indiana.

We discussed the patent situation of rapidly quenched REPM alloys such as the Magnequench material. Dr. Kamino has apparently filed a Japanese patent for producing various transition-metal-lanthanide-metalloid alloys by a rapid quenching technique which, if granted, may in fact predate some of the patent claims of General Motors Company and others, at least in Japan. It will be interesting to watch as the patent situation regarding the rare-earth-iron-borides and their derivatives slowly evolves.

Hitachi Metals, Ltd. (HML)

We had an opportunity to visit with persons involved in the rare-earth magnet development and production at the Kumagaya, Saitama, laboratories of HML. After a brief tour of their laboratory facilities and inspection of HML's magnetic product exhibit, we spent most of our time in conversations with research personnel. We discussed in considerable detail recent research and materials development efforts at HML, new magnet products, and again reported on our own work at the Army ET&D laboratories and the University of Dayton. Our principal hosts were Dr. Hideki Harada, manager of the Electronic and Magnetic Materials Laboratory and research director of HML, and Masaaki Tokunaga, manager of the fifth R&D section and leader of the rare-earth magnet development team. We also interacted at some length with Shogo Tanaka, assistant general manager of the Engineering Department; Shigeho Tanigawa, a senior magnet researcher; and Shinya Okayasu, a senior engineer in the International Division of the Planning Department. Our common interests involved alloy and magnet development work in the 2-17 alloy area and in modifications of Nd-Fe-B that will make this material more stable and useful at elevated temperatures. HML has developed a new low-temperature-coefficient 2-17 magnet "doped" with the heavy rare earth Gd. We received tentative data sheets for two versions of this product with different doping levels.

In the rare Re-Fe-B magnet area, HML is now a producer of sintered magnets under a license from the Sumitomo Special Metals Co., and experiments with the alternative production technology, rapid quenching, are also in progress. Like other manufacturers, Hitachi has introduced dysprosium and cobalt as minor alloying elements to improve the properties at elevated temperatures, and a magnet containing both is now in pilot production. Beyond this, the effects of niobium, aluminum, and gallium on such magnets have been studied and results reported at the INTERMAG Conference. Ga and Nb appear to go into a grain boundary phase, raising the temperature at which the intrinsic coercive force reaches near-zero values. This temperature, rather than the Curie point of the main phase, determines the upper use temperature limit of such a magnet, so these doping elements have definitely improved the elevated temperature behavior of the magnets. On the more scientific side, the Hitachi workers are intensely interested in clarifying the physical origins of the coercivity and its temperature dependence and--like researchers at the University of Dayton--seem convinced that ferromagnetic grain boundary phases play a major role. A cooperative experimental project along these lines is in progress between our laboratories. HML has also sponsored efforts at, and supplied samples to, other academic laboratories, including the Massachusetts Institute of Technology and the Technical University Vienna. This is reflected in papers at the 1987 INTERMAG and other recent publications.

Hitachi Metals, Ltd. has long included in its manufacturing programs the traditional major permanent magnet types, Alnico and hard ferrites, and it has one of the world's largest, highly automated and efficient ferrite production plants. HML also has a large plant to produce sintered $SmCo_5$, Sm_2Co_{17}, and now Nd-Fe-B based magnets in Kumagaya. Similar and partly complementary production facilities exist at the Hitachi Magnetics Corporation in Edmore, MI, a plant that Hitachi purchased from the General Electric Company over a decade ago. These two facilities, taken together, probably have the largest output of rare-earth magnets in the world. HML builds many components involving permanent magnets, such as linear actuators for computer disk drives, the rolls (or "magnetic brushes") for transporting toners in xerographic copying machines, and traveling-wave tube components. HML also produces a variety of metallic and oxidic soft magnetic materials (but not transformer sheet steel) and many products made from these. They include, for instance, microwave components, chokes, magnetic recording heads, and magnetic garnets for use in high frequency and magneto-optical devices. HML is also a large producer of the ferrite powders used to carry the toner in copiers, which have to have critically balanced magnetic and electrostatic properties, and since another Hitachi division (Maxell) is a major manufacturer of magnetic recording media (audio and video tapes and computer disks), work on recording materials is also an important concern at HML.

Shin-Etsu Chemical Company, Ltd.

Shin-Etsu (S-E) is a medium-size chemical company with a broad spectrum of products. The plant we visited is located in Takefu, a small town in the Fukui district on the west coast of Honshu, on the Sea of Japan. S-E has a number of production plants in several locations in Japan, and it is apparently also a partner in a number of international joint venture companies. Shin-Etsu has long been a manufacturer of rare earths in separated form, and this led the company into the rare-earth permanent magnet business about 12 years ago. S-E is by now probably the Japanese manufacturer with the largest REPM sales volume, but its production program includes no other permanent magnet materials. More generally, S-E has a large business as a supplier of basic materials for the electronics industry, including silicon single crystal wafers, garnet crystal substrates, and optical quality quartz.

Our principal hosts at Shin-Etsu were Dr. Yoshio Tawara, the general manager of R&D in electrical and magnetic materials, and K. Ohashi, who heads a group of 11 people involved in permanent magnet research and development. M. Honshima is the manager of magnet production, which now employs about 300 workers. Dr. Tawara was among the first Japanese scientists to become active in the field of rare-earth magnets. Working at the Matsushita Company at the time, he was coinventor of the process that allows magnetic hardening of RE-Co alloys by adding copper and precipitation hardening. In 1976 he spent 9 months at the University of Dayton then went to Shin-Etsu to build up and manage the production of a large family of magnet types derived from that invention. For years, S-E's production program comprised only sintered magnets based on the rare earths Sm and Ce, combined with Co, Cu, Fe, and in some products Mn. The magnets can all be classified as "2-17" types. Recently, under license from Sumitomo Special Metals Company, sintered Nd-Fe-Co-B has also been added to the product line. Shin-Etsu's REPM business has apparently been excellent for years and is rapidly growing, at about 25 percent per year. The present sales volume is about ¥680 million per month; it is expected to double next year due to the addition of Nd-Fe products. Most of the sales appear to be to the Japanese electronics industry (consumer electronics and computer peripherals), with increasing sales for electric motors and actuators that find uses in automobiles and appliances. The REPM business is highly individualized: S-E produces about 600 different shapes of magnets now, many of which are frequently changed. Such a product line requires many people experienced in magnetic device design and optimization to assist customers. S-E appears to be well staffed and equipped for this mode of operation, employing about 20 people that are engaged in magnetic circuit design and analysis. S-E has constantly worked to expand and renew its REPM production facilities. There are three magnet plants now, with the oldest one soon to be closed. The second plant has been in operation for about 2 years, and a third is in partial operation. The company is planning to build a separate, large new plant exclusively for the production of sintered Nd-Fe(Co)-B magnets.

Shin-Etsu very openly showed us its REPM Plant 2 and laboratory facilities; we also saw some sections unrelated to the magnet production. Thus, S-E continued a rare tradition of openness that visitors to Takefu have enjoyed on previous occasions.

Shin-Etsu has a significant advantage over some other magnet manufacturers in that it is a chemical company that processes, separates, and purifies the rare-earth metals needed in the REPM production. It has also set up a magnet scrap reprocessing plant that contributes 1 to 2 tons per month to the Sm supply (which is a relatively minor fraction of the overall consumption). Shin-Etsu does not own ore sources but appears to be looking for them. S-E buys samarium oxide in Japan, France, and the United States that is derived from mines in Malaysia, Africa, the United States, and elsewhere. To assure a continuing supply of Sm (and the heavy RE) in the face of a worldwide shortage, Shin-Etsu has arranged joint ventures with a Canadian mining company to get heavy rare earths as a by-product of uranium and with the W.R. Grace Company to build a separation plant in Chattanooga, TN, that will also supply a heavy RE mixture. For further separation of this material, including the extraction of Sm for permanent magnets, Shin-Etsu has just built a new, modern rare-earth separation plant in Takefu.

We saw a number of specific pieces of unique production equipment and analytical laboratory tools. For details about these, the reader is referred to a 1985 article in which C.D. Graham, Jr., reported on his earlier visits with Shin-Etsu and other Japanese magnet companies.* Prof. Graham of the University of Pennsylvania reports the same pleasant experience of openness and hospitality at Shin-Etsu.

Sumitomo Special Metals Company, Ltd. (SSMC)

The next magnet manufacturer that we visited was the Yamazaki Works of SSMC, located between Kyoto and Osaka. This company is a traditional and very well known manufacturer of all kinds of permanent magnets. It has a very strong and productive R&D contingent under the management of Dr. Akira Higuchi. It was SSMC that developed the first practical neodymium-iron-based magnet and a powder metallurgical sintering process for its production, which is now being emulated worldwide. SSMC shares with the General Motors Corporation the credit for having discovered the utility of the $R_2Fe_{14}B$ compounds for permanent magnets and for having introduced such magnets into commercial production beginning in 1984. There still is much scientific and inventive activity in this field (see INTERNATIONAL MAGNETICS CONFERENCE), and the Sumitomo team continues to make important contributions.

At SSMC, we did not see laboratories or plant facilities (the "Neomag" production plant is located several hundred kilometers from Kyoto), but we had extremely interesting conversations with members of the scientific staff. Our principal host

*Graham, C.D., Jr. 1985. Magnetics laboratories in Japan. *Scientific Bulletin* 10(2): 146–59.

was Dr. Masato Sagawa, manager of the Nd–Fe research group. Dr. Satoshi Hirosawa gave a very interesting discussion of his experiments regarding the origin of coercivity in Nd–Fe–B sintered magnets. He maintained that the mechanism is controlled strictly by domain nucleation, with no significant contribution from wall pinning at grain boundaries. In this respect, my conception of the mechanisms differs from that described by Dr. Hirosawa; we shall have to conduct experiments to resolve these differences. A number of other research staff members were present and contributed actively to a very lively information exchange on scientific and technical matters concerning rare-earth magnets. Among the others were Masiji Endo, Mr. Miyamoto, Hiroshi Nagata, and the magnetic circuit designers, H. Takabayashi and K. Makita.

Unfortunately, the competition for the attention of our hosts was great; they had a constant stream of foreign visitors taking the opportunity offered by INTERMAG to visit Sumitomo. Nevertheless, our visit was very interesting and productive, and the kind personal hospitality of Dr. Sagawa made it particularly memorable.

Toshiba Research and Development Center (TRDC)

The central research center of the Toshiba Corporation is located in the city of Kawasaki, not far from Tokyo. Our visit there was organized by Dr. Koichiro Inomata, chief research scientist in the metals and ceramics laboratory. The full workday available was barely adequate to get a superficial impression of the many activities of interest to us. The tightly organized program began with a fairly formal welcome by Fumio Miyashiro, the senior manager of the metals and ceramics laboratory, who gave an overview of Toshiba's business activities; the organization of the R&D center; and more specifically the work on materials, devices, and systems involving magnetics. We also had an opportunity for a relatively superficial tour of several specialized materials laboratories, those concerned with permanent magnets, amorphous magnetic alloys, new ceramics and their application development, barium ferrite tape for perpendicular recording, and superconducting ceramics. We were also given a tour of the Toshiba Science Institute, a kind of technological museum that has many impressive and expensive displays with emphasis on systems such as industrial robots, magnetically levitated trains, and the modern electronic household of the future. While advertising the accomplishments of Toshiba is an important part, the institute seems to be largely designed to interest young people in studying science and preparing for technological careers. It appears to be open to the public with many school classes coming through. Many of the displays are hands-on type. There is also a very well done section on the history of electronic technology, explaining the contributions of scientists and engineers worldwide.

The Toshiba Corporation has about 70,000 employees and the R&D Center is correspondingly large, modern, well equipped, and staffed. The center is over 25 years old. It employs about 1,750 persons, has 10 major laboratories, and has a separate very large scale integration (VLSI) research center in which 250 people work on the implementation of VLSI of electronic devices and circuits. The work we discussed is performed in Mr. Miyashiro's metals and ceramics laboratory, which has subdivisions on structural and functional materials. In particular, we heard from T. Mizoguchi and A. Tsutai about their recent studies on permanent magnets in the Nd–Fe–B system, which includes the substitution of cobalt and gallium in attempts to increase the utility of the materials at elevated temperatures. Dr. Inomata, who also has a long history of accomplishment in permanent magnets, has recently concentrated on amorphous magnetic alloys with applications as soft magnetic core materials and in magnetic recording. Mr. Yokoyama discussed Toshiba's efforts in developing magnetic recording media, together with Osamu Kubo of the recording media and systems development department. They spoke of the impending introduction of vertical recording media in the form of flexible disks, thermomagnetic recording, and magneto-optic readout media.

Of the activities outside the field of magnetic materials, it was particularly interesting to see that TRDC has made considerable progress in producing useful shapes of the new superconducting ceramics with high transition temperatures. Since Toshiba has long been promoting applications of superconducting electromagnets and is a producer of intermetallic wires and solenoids for these purposes, it is not surprising that methods of using the Y-Ba-Cu-O materials for magnets that would function in liquid nitrogen are now in the foreground. We were shown wires of 1 mm diameter fabricated by encapsulating the oxide powder in a copper alloy jacket and drawing or swaging it into wire; flat ribbons were also made this way by rolling the wire. Experimental coils made by winding and then sintering such wires are said to have a current carrying capacity of 130 A/cm^2 at 77 K, which is still orders of magnitude too small for practical solenoid magnets. However, the upper critical field is between 100 and 200 kOe at 4.2 K and about 40 kOe at 77 K, and the critical temperature is 96 K. Toshiba scientists are confident that rapid progress toward practical LN_2 superconducting magnets will be made in their laboratory. Other active projects in the metals and ceramics laboratory of interest to us involve ceramic substrates for semiconductor devices with high thermal conductivity (aluminum nitride), high strength/high temperature structural ceramics (silicon nitride), and amorphous transition-metal-based alloys for magnetic applications such as transformer cores in switching power supplies, sensors, etc.

Tohoku University

We also had an opportunity to visit the Functional Materials Laboratory of the Materials Science and Engineering Department of Tohoku University at Sendai. Our visit there coincided with the International Symposium on the Physics of Magnetic Materials, so we were again competing with other visitors and events. We were grateful that Prof. Motofumi Homma and Dr. Masao Okada were willing to spend time with us. They assembled a group of graduate students who work on several aspects of rare-earth permanent magnet R&D. The emphasis appears to be on R-Fe-B magnets in which a part of the Nd is replaced by Pr and/or Ce. The objective of such work is to further broaden the raw materials base for the RE component and to make the RE cheaper by avoiding an expensive separation step (Pr from Nd) and learning to use as much as possible of the inexpensive and plentiful rare earth cerium. Current investigations involve the effects of these and additional elements on the magnetic properties, particularly the coercivity. There is also an effort to prepare RE-Fe-B alloy particles suitable for use in polymer-bonded magnets. Two important problems in this respect are the dramatic loss of coercivity when RE-Fe-B alloys are ground into powders and the rapid corrosion of such particles' surfaces with a corresponding deterioration of magnetic properties. The group presented papers at INTERMAG relating to these problems. It appears that these efforts to produce better and cheaper bonded magnets are supported by Japanese magnet manufacturers trying to introduce polymer-matrix Nd-Fe-B based magnets.

Other continuing efforts of this group are concerned with Fe-Cr-Co permanent magnets, attempts to improve the properties of barium ferrite magnetic oxides (again for use in bonded magnets), and studies of Sendust-type soft magnetic alloys (temperature dependence of magnetic properties and magnetic aftereffect). The group also works on the new ceramic superconductors and on composite ceramics combining lead titanate and titanium dioxide, which show a large change in electrical resistivity at a critical temperature associated with a phase transition. This "thermistor-like behavior," previously exhibited only by barium titanate, promises to have engineering applications.

The MG Company

Our last visit was with a company, located in Rifu-machi, Miyagi-gun (MG) near Sendai, that produces polymer-bonded, rare-earth-cobalt-based permanent magnets. Our principal host there was Dr. Masaaki Hamano, who was assisted by Masaharu Okudera. We also had the opportunity to meet the company's president, Masashi Watanabe. This company is basically in the business of processing plastics for various structural and electronic applications, and in particular specializes in injection molding. Dr. Hamano, who did his university research on 2-17 type magnet alloys, introduced polymer-bonded RE magnets into the production program of the company, and they appear to be commercially quite successful. The magnetic material is a precipitation-hardened, 2-17 RE-Co-Fe-Cu alloy that is purchased as a powder and molded into a variety of mostly small magnets or into components combining magnetic and structural materials in one piece. We were shown a very modern and highly automated plant for the injection molding of plastics but did not see the magnet production. It appears that in this business mold and tool design and construction are the keys to success. The company has an excellently equipped department for computer-aided tool design; has machine shops with versatile, computer-controlled machine tools; and fabricates all molding tools in-house. Some of the tools we saw are extremely complex; they seem real miracles of clever design and precision machining. We understand that the company is preparing to open production plants in Mexico and in the United States (in Georgia), but apparently these will be general plastic processors rather than magnet plants.

Seiko-Epson Corporation

We had scheduled a visit to another plant producing polymer-bonded permanent magnets of the REPM type, namely, the former Suwa Seikosha plant located in Suwa, Nagano-ken. We had to cancel this visit because we ran out of time. However, we had an opportunity to meet the manager of research and development of this plant, Dr. Tatsuya Shimoda, and his associate, Kouji Akioka, in Tokyo on a social basis. Under Dr. Shimoda's leadership, this company has developed a variety of manufacturing processes for epoxy-matrix magnets with properties covering a very wide range (energy products from 2 to 17 MGOe). Products vary from isotropic to highly oriented, including radially aligned magnets, and are processed by diepressing, impregnation of prepressed compacts, and by injection molding. Seiko-Epson has also developed its own alloys with very high remanence, which allowed the company to achieve record energy products. Seiko-Epson probably has the largest share of the bonded REPM market in the world at this time. The company has been aggressively pursuing sales in the United States and has a strong and successful presentation by a U.S. company. It is our understanding that a plant in Portland, OR, will soon begin magnet production in the United States, apparently under an Epson license rather than direct ownership. This emphasizes the previously mentioned fact that matrix-type rare-earth magnets are now finding broad acceptance among permanent magnet users and that this technology is in a phase of explosive expansion.

ACKNOWLEDGMENTS

We are particularly grateful for the assistance of two persons who helped to make this trip easy, enjoyable, and productive. Dr. Edward S. Chen, associate director of the Army Research Office/Office of Naval Research/Air Force Office of Scientific Research (ARO/ONR/AFOSR), Liaison Office Far East in Tokyo, provided valuable and very personal support. Tsunehisa Kurino, the general manager of the Society of Non-Traditional Technology, also in Tokyo, contacted all our host institutions, coordinated our visits, made travel arrangements, and helped in many other ways. Mr. Kurino and the director of the society, Prof. Hideo Kaneko, also organized an evening of lectures for a large group of scientists and engineers from the greater Tokyo area, thus giving us an opportunity to meet many Japanese workers in our technical fields of interest before starting the tour of laboratories.

Karl J. Strnat, born in Vienna, Austria, received an associate degree in mechanical engineering in 1948, a master of science degree in engineering physics in 1953, and a doctor of science degree in electrical engineering in 1956 from the Technical University Vienna. Dr. Strnat was assistant for research and teaching at the Technical University Vienna for 3 years before joining the Air Force Materials Laboratory, Ohio, in 1958, where he held various positions including section chief and head of a magnetics research group. In 1968 he joined the University of Dayton, Ohio, as F.M. Tait Professor. He now teaches magnetics and field theory courses in the electrical and materials engineering programs, heads the university's Magnetics Laboratory, directs graduate research, and manages contractual research and development on hardmagnetic materials and their device applications. Dr. Strnat's research on the magnetic properties and metallurgy of rare-earth/transition-metal alloys in the 1960s started the development of rare-earth permanent magnets. $SmCo_5$ and its derivatives have since become important commercial magnet materials. He holds seven U.S. and numerous foreign patents in the field of permanent magnets and magnetic alloys. Dr. Strnat is a fellow of the IEEE and a member of the American Physical Society, the ASM International, and the European Arbeitsgemeinschaft Magnetismus.

MATERIALS ENGINEERING RESEARCH IN TAIWAN

Thomas W. Eagar

This article highlights observations made on visits to five major research and development institutions in Taiwan, which is rapidly emerging as a major center of manufacturing in the Far East. The research efforts and facilities at Tatung Institute of Technology, National Tsing Hua University, Materials Research Laboratories, China Steel Corporation, and China Shipbuilding Corporation are described.

INTRODUCTION

Along with Korea and Singapore, Taiwan is rapidly developing as a manufacturing center of increasingly sophisticated products. The following notes represent observations made of those developments at five institutions on a recent trip to Taiwan.

TATUNG INSTITUTE OF TECHNOLOGY

With 21,000 employees and $1 billion in annual sales, Tatung Company is the largest employer and the second largest company in Taiwan. Established in 1918, Tatung Company is active in home appliances, electronics, and industrial electrical equipment. Tatung's overseas sales have quadrupled over 4 years to about 30 percent of its business.

In 1951, Tatung Company started its own 2-year college. In 1963, the college expanded to 4 years. Today there are 1,200 students and 150 faculty members with doctoral programs in electrical engineering, mechanical engineering and chemical engineering. Masters degrees are offered in business, information engineering, and materials engineering. There are nine undergraduate programs, with the most recent addition the Department of Bioengineering in 1986.

Any student in Taiwan can apply to Tatung Institute of Technology. The tuition is greater than the public universities but less than most private universities because of the financial support received from Tatung Company. Upon graduation, about 20 percent of the students find employment with the parent company. All students are required to learn both Japanese and English. To enforce this, some upper level classes are taught in Japanese, while many of the theses are written in English.

The Materials Engineering Department was established in 1983. Currently it has 10 full-time and 8 part-time faculty members, half of whom studied in the United States. The department receives $1 million per year of new equipment from the parent company. Current facilities include laboratories for metallography, x-ray, SEM, mechanical testing, thin films, ceramic and metal powders, magnetic materials, corrosion, casting, heat treatment, composite materials, non-destructive testing (NDT), and scanning transmission electron microscopy (STEM). Most of the equipment is equal or nearly equal to that found in most large universities in the United States.

One of the reasons for the excellent research facilities at Tatung Institute of Technology is that the institute serves as the research laboratory for the parent company. In this way the research equipment coming to the university avoids the usual government tariffs that an industrial laboratory must pay. Each professor is free to work on his own projects, but each also has the opportunity to take development grants from the operating divisions of the parent company. There are more than enough projects to keep each faculty member busy on company-related research. In addition, the institute is adjacent to the company's main office and several production facilities. The company's 26 computer-aided design/manufacturing (CAD/CAM) engineers work on the CALMA VAX 11/780 system available at the institute. The electrical engineering students assist in the production of silicon crystals and wafers in the adjacent factory. The work at the institute is not far behind the industry standard in Taiwan. For example, the institute uses 3-micron technology and up to 1,000 gates for manufacturing silicon circuits, while the industry standard is 2 microns with 5,000 gates.

In summary, Tatung Institute of Technology offers an intriguing blend of academic and industrial research. The relationship allows the institute to acquire excellent facilities and practical research problems while the parent company benefits from an expanded pool of researchers. It represents a mode of university-industry cooperation that was once found at a number of places in the United States but has declined to near extinction. The results at Tatung Institute of Technology confirm that this approach can still work to the mutual benefit of both industry and the university.

NATIONAL TSING HUA UNIVERSITY

National Taiwan University and National Tsing Hua University represent the two finest engineering schools in Taiwan. National Taiwan University is larger and more diversified, while National Tsing Hua is predominately an engineering school with about 3,000 students.

The Department of Materials Science and Engineering is 15 years old. There are 250 undergraduates and 100 graduate students of which nearly 40 percent are doctoral students. The research facilities are excellent by any standard. The major laboratory facilities are:

- Electron Microscopy Lab: JEOL-200 CX STEM, JCXA-733 electron microprobe, JEM-100B TEM, and JSM-U3 SEM

- X-ray Lab: Shimadzu XD-5, Philips 120K5B x-ray diffractometer, Rigaku 9579 x-ray fluorescence analyzer

- Atomic Emission Spectroscopy Lab: Shimadzu GVM-1000 atomic emission spectrophotometer

- Surface Analysis Lab: Perkin-Elmer PHI-595 Auger/ESCA surface analyzer

- Optical Metallography Lab: About 10 optical microscopes with photographic attachments

- Powder Metallurgy Lab: Hot press, sintering furnace with atmospheric control

- Electronic Materials Lab: Electron gun evaporator, ellipsometer, vacuum furnace

- Corrosion and Electroplating Lab: PARC Model 173 potentiostat/galvanostat, programmer, hull cell, salt spray tester, pulse plating set

- Mechanical Property Lab: Instron 1115 tensile tester, impact tester, hardness tester, fatigue tester

- Melting and Casting Lab: 100-kg vacuum furnace, air furnace

- Materials Processing Lab: Cold-hot 1/4-ton forger, 50-hp rolling mill

- Heat Treatment Lab: Nitridation furnace, carburization furnace, high temperature furnace, intermediate temperature furnace, low temperature furnace

The areas of current research, which are very broad and are expanding, are as follows:

A. Characterization

(1) Mechanical properties
(2) Surface analysis
(3) Elemental analysis
(4) Structural analysis

B. Metals

(1) Light metals: Al-Zn-Mg alloys, Al powder metallurgy and its composites, Al-Li alloys
(2) Ferrous metals: Al-Mn stainless steels, dual phase steels
(3) Special alloys: superalloys, Cd-Cu alloys
(4) Investment casting

C. Electronic Materials

(1) VLSI materials: metal silicides
(2) Compound semiconductors: CdTe, GaAs, MCT
(3) Crystal preparation and processing: single crystal growth, epitaxial growth, ion implantation
(4) Thin film preparation: magnetic thin-film, coatings of electronic materials
(5) Magnetic materials: SmCo magnets

D. Ceramics

(1) Ceramic powder preparation and processing
(2) Electronic ceramics: MnZn ferrites, PZT, $BaTiO_3$, $SrTiO_3$, spinel, ceramic sensors
(3) Mechanical ceramics
(4) Glasses

E. Corrosion and Surface Technology

(1) Stress corrosion and corrosion fatigue
(2) High temperature corrosion
(3) Surface technology: composite coating, alloy electroplating, electroless plating, organic coating, anodizing
(4) Corrosion and corrosion prevention of power plant and reinforcement in concrete construction

The Government has identified materials science and engineering as a major growth area. There are currently 21 faculty members (two-thirds of whom were educated in the United States) and searches are in progress for 4 more. It is clear that with such a large group of faculty and students equipped with modern facilities, National Tsing Hua University will produce some exciting research in coming years.

MATERIALS RESEARCH LABORATORIES

The Materials Research Laboratories (MRL) was started in 1983 with 70 people. Today it occupies a new 19,000-m^2 building (in addition to a 4,000-m^2 Metallurgy Experimental Plant) and has a staff of 430 with plans to expand to 600 in the future. There are 40 staff members studying corrosion alone.

MRL is one of six groups of the Industrial Technology Research Institute (ITRI). ITRI was formed in 1973 as a nonprofit institution intended to bridge the gap between basic research and commercial production. ITRI lists applied research, technology development, pilot production, and technology transfer as its major functions. The six research groups and their general areas of study are as follows:

A. Union Chemical Laboratories

- Chemical process technology and development of high value-added products
- Industrial pollution abatement technology and energy-efficient chemical process development
- Development of engineering plastics and high performance polymers
- Development of engineering plastics and high performance polymers
- Plastic processing, mold design, and synthetic fiber-spinning technologies
- Exploratory research on biotechnology

B. Mechanical Industry Research Laboratories

- Computer-aided design, manufacture, test, and management information system
- Industrial robots and flexible manufacturing systems
- Machine tools and industrial production machines
- Automatic control systems and key components
- Ultra-precision machining processes
- Power engine research, inspection, and test

C. Electronics Research and Service Organization

- Very large scale integration design and manufacture
- IC common design center to help clients design IC on their own
- Computer system software
- Computer peripherals and intelligent terminals
- Digital TV technology
- Digital local area networks

D. Energy and Mining Research/Service Organization

- Energy conservation and efficiency enhancement of manufacturing processes
- Architectural energy conservation
- Alternative energy sources: solar energy, wind power, biomass, and geothermal
- Remote sensing and engineering geology
- Mineral exploration in cooperation with organizations at home and abroad

E. Materials Research Laboratories

- Metallic materials
- Casting, forging, and powder metallurgy technology
- High polymer and composite materials
- Fine ceramics materials
- Second-generation semiconductor materials
- Sensing materials
- Corrosion prevention
- Services of material inspection and information

F. Center for Measurement Standards

- Maintaining national measurement standards

- Services to a network of secondary laboratories for international calibration traceability and national measurement system
- Upgrading the measurement technology

The oldest part of the Materials Research Laboratories is the Metallurgy Experimental Plant, which was established in 1973 as part of the Mechanical Industry Research Laboratories prior to establishment of the MRL 10 years later. The Metallurgy Experimental Plant specializes in ferrous and nonferrous castings as well as research of various casting techniques. Facilities include a 1-ton electric arc furnace and smaller vacuum melting, lost wax, induction, and diecasting equipment as well as associated NDT and quality assurance (QA) equipment. Typical parts produced include A356 aircraft aluminum parts, IN713 nickel-based turbochargers, 4340 automotive parts, HK40 high-temperature components, copper, brasses, magnesium, cast iron, stainless steels, and the like.

Optoelectronics research at MRL emphasizes GaAs and GaP growth and device fabrication. Specialty polymers research includes photo resists, flexible circuit boards, and PVDF, a piezoelectric polymer film. Research on specialty alloys includes extensive work on shape memory alloys and rapid solidification processing. Composites have emphasized use of graphite fibers with several successful commercial developments.

Most of the magnetic materials research involves hard magnetic materials. The fine ceramics work appears to be relatively new, [illegible] difficult to judge the [illegible]. The corrosion test facilities are extensive. Most of the research in this area is sponsored by [illegible].

Currently 75 percent of MRL's research funds come from the Government and only 25 percent from industry; however, this is somewhat misleading because many of the larger industries in Taiwan are owned by the Government. In any case, the new MRL facilities and their rapid growth are quite impressive. As MRL becomes fully established, many useful developments should result from this major investment.

CHINA STEEL CORPORATION

China Steel is one of 10 "brother" industries owned by the Taiwanese Government. The integrated steel plant was begun in 1977 with assistance from U.S. Steel Corporation (now USX). Current production is 3.25 million MT per year with expansion to 5.65 MMT in April 1988 and an ultimate goal of 8 MMT. China Steel currently claims to use the second lowest manhours per ton of steel after Pohang Steel in Korea. As a result, China Steel is very profitable.

Most of the early growth was based on common grade mill products including bar, plate, and hot and cold rolled sheet. As the capacity expands, China Steel is moving into higher quality products. An accelerated cooling line is being established for plate steel with help from a European company. The Japanese steel companies see China Steel as a major threat and hence are unwilling to assist [illegible] new ventures.

The Research and Development Department at China Steel began in September 1977 with 20 people. There are 2[illegible] people now with a 10-percent expansion planned over the next several years. One-third of the staff work on product development, although only 10 are working on new materials. Expansion [illegible] the New Materials Department

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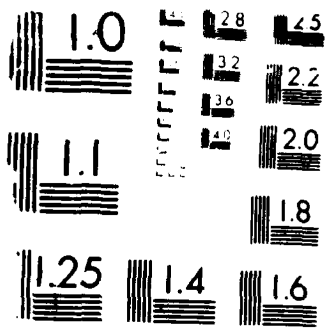
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to 66 people is planned with work on polymers, chemicals, carbon fibers, new metals, rapid solidification processing (RSP), and magnetic materials. A major concern of the past has been training of production personnel as Taiwan had no major steel production facilities before China Steel was established and the entire plant was run by novices. Now with 10 years of experience, the goal is to develop newer, higher technology products.

The research facilities are very good and, with the high profitability, there is virtually no restriction on acquisition of new equipment. Although the Research Department at China Steel spent the first decade getting established, there is no doubt that it will broaden its influence in the future.

CHINA SHIPBUILDING CORPORATION

China Shipbuilding Corporation (CSBC) is another of the 10 "brother" companies operated by the Taiwanese Government. In contrast to China Steel, CSBC's newest shipyard was not built with significant foreign assistance. The older shipyard in Keelung was started in 1945, while the Kaohsiung yard was completed in 1976. The Kaohsiung yard is now the major facility with a 1,000,000-ton drydock equipped with two 350-ton cranes. Products range from naval patrol boats to half-million-ton cargo ships to offshore platforms. Unfortunately, the depressed worldwide shipping market is severely affecting the company. Attempts have been made to bring in onshore construction, but Taiwan as a country cannot make use of the extensive facilities available at Kaohsiung. Overall, the yard appears to be operating at about one-half of capacity.

In order to compete more effectively, numerous changes have been made over the past few years. Manual welding has dropped from over 50 percent to less than 20 percent, making Kaohsiung perhaps the most "automated" shipyard in the world as far as welding is concerned. The proximity of China Steel and Taiwan Machine Manufacturing Company (another "brother") as next-door neighbors helps to lower costs, but it is still not enough. CSBC cannot survive as it is without an increase in the world's shipbuilding.

SUMMARY

Although limited to only some of Taiwan's materials research and production facilities, these visits clearly show a dramatic rise in materials research in Taiwan over the past decade. Both the research and the production facilities are impressive by any standard that one cares to use. Although much of the work of the past has been directed toward bringing Taiwan up to world-class standards, that task is largely complete. Future work will no doubt expand into new areas not previously covered anywhere in the world. Just as the more developed countries have learned to respect the work done in Japan over the past 20 years, so should they learn to respect the work that is beginning to emerge from Taiwan.

Thomas W. Eagar, recently a liaison scientist with ONR Far East, is a professor of materials engineering at the Massachusetts Institute of Technology. Dr. Eagar's professional interests are broadly in manufacturing processes for metals and ceramics with more specific interest in welding and joining technology.

PHASE, ELECTRON HOLOGRAPHY, AND A CONCLUSIVE DEMONSTRATION OF THE AHARONOV-BOHM EFFECT

Akira Tonomura and Earl Callen

In electron holography an electron wave is divided into two beams. One beam is transmitted through the object to be investigated and the other reference beam is not. The two beams are recombined and are caused to impinge on photographic film. This photographic image is a hologram of the object. An optical image is reconstructed by shining coherent light on the hologram. The interference pattern in the hologram results from phase shifts in the electron wave caused by electrical and magnetic potentials in the object through which the electron has propagated. Fringe patterns in the reconstructed image represent electrical potential topographical projections (which conform to thickness changes in the sample) and magnetic field lines (magnetization). Electron holography gives incontrovertible proof of the Aharonov-Bohm effect.

INTRODUCTION

Photographs record the relative intensities of light reflected from various parts of an object. There is more information in the light stream than the intensities; there are also the relative phases. To break through the resolution limit, Gabor (Ref 1) devised the ingenious idea of holography, using this phase information. That was in 1949. For holography to work, a coherent, collimated source beam is indispensable. Except for a number of brave and determined exceptions, light holography had to wait until the advent of lasers in 1960. Electron holography has been slower and more evolutionary in development, but now there are available field-emission electron microscopes with such a high degree of beam coherence that 3,000 interference fringes can be observed.

ELECTRON HOLOGRAPHY (Ref 2)

In light holography, a light wave scattered from an object is brought to interfere with a reference wave, and the interference pattern is (perhaps) magnified and recorded on film. This is the "hologram." Shining monochromatic light on this film--the light can be of any wavelength--reconstructs wavefronts that are copies of the original. In the first step of electron holography (see Figure 1) an electron wave scattered from an object is brought to interfere with a reference electron wave. The pattern is enlarged by electron lenses (magnifications of 1000 are attained) and the interference pattern is recorded on film. The second step (see Figure 2) is as before--a light beam of any convenient wavelength incident on the film reconstructs wavefronts similar in shape to the original electron wavefronts. From this point forward, versatile optical techniques can be used rather than the difficult electron optics. Both light and electron holography were conceived of by Gabor (Ref 1).

In the first stage of electron holography coherence is assured, since only one electron at a time is in the chamber, but collimation is a problem. The tungsten tip must have an extremely fine point. Electrostatic forces tend to disperse the beam. An accelerating voltage of 150 kV is used. This corresponds to an electron deBroglie wavelength of 0.03 Å. It is interesting to note that in the reconstruction stage the wavelength of the He-Ne laser light, 6,328 Å, is 2×10^5 as large.

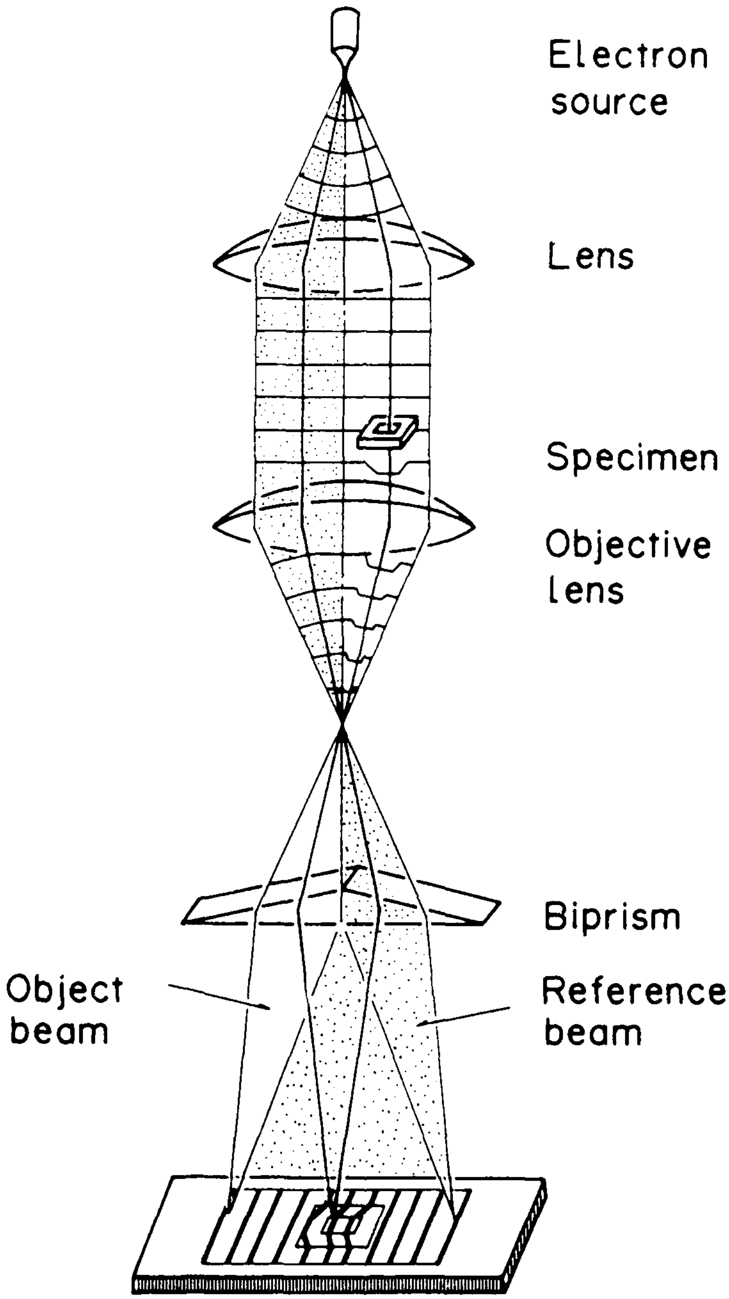


Figure 1. Schematic representation of hologram formation by interfering electron beams.

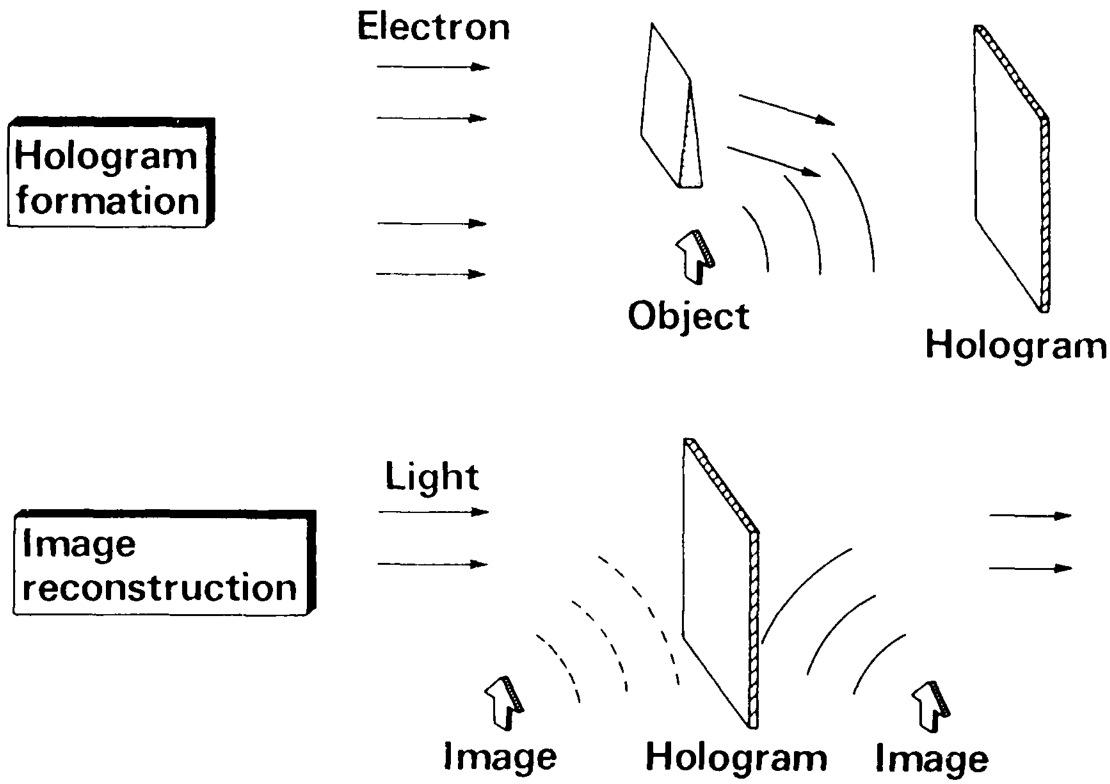


Figure 2. Holography is a two-step process. First a hologram is formed. An image is reconstructed by shining light on the hologram.

Perhaps the most important application of electron holography is in interference electron microscopy (Ref 2). When the directions of the reconstructed object wave and a reference plane wave are the same in the optical reconstruction system, the interference micrograph is called a contour map. From a contour map alone one cannot tell whether the wavefront is advanced or retarded. When the direction of the reference plane wave differs from that of the object wave in the optical reconstruction system, the micrograph is called an interferogram. An interferogram allows determination of the sense of the phase shift, and hence the direction of an electric or magnetic field.

To understand how this works consider Figure 3. In the next section on the Aharonov-Bohm effect, we give a quantum mechanical argument, appealing only to potentials. But to "feel" what is going on we do better to cheat a little and use our intuition about forces. The top of the figure shows two electrons descending vertically, one on the left and one on the right. In the field-free regions at the top the electron wavefunctions are plane waves and the wavefronts, the surfaces of constant phase, are horizontal planes. The electron on the left next enters an electric field and is deflected by force $-eE$. Since the force is normal to the equipotential lines, the wavefronts rotate about an axis along an equipotential line. On the right the electron undergoes force $-ev \times \mathbf{B}$, and the wavefronts rotate about an axis along a magnetic field line.

The lines of constructive interference, and hence the fringes in contour maps--separated in phase by 2π of course--pattern electrical equipotentials and magnetic field lines. In the next section we shall show that the phase separation between adjacent fringes is, in the electrical case, equal to the product (voltage in a region) times (time spent in that region). Since the electron's speed is extremely large compared to its change in speed from region to region in the scatterer, contour lines are equal voltage steps, to high accuracy. The magnetic case is even more informative: adjacent contour lines represent flux h/e (4.1×10^{-15} Wb). Figure 4a is a contour map of a cobalt fine particle, about 1,000 Å on an edge and 550 Å thick. The contour lines close to the edges are electrostatic equipotentials; they show that the thickness rises linearly near the edges. The inner half-dozen rings are not equipotentials. Interferogram analysis, to be discussed next, shows that these inner rings are in fact magnetic field lines. The particle is actually flat through the central region.

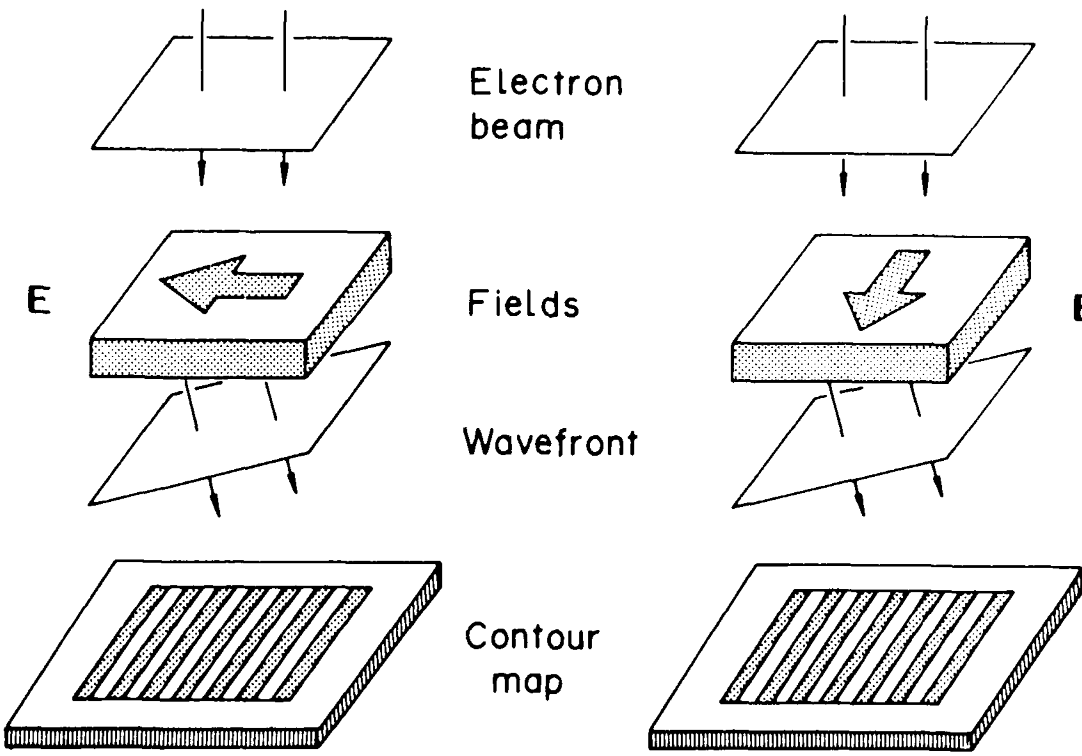


Figure 3. Semiclassical description of contour map formation. Rotation of the electron wave propagation vector by electric and magnetic fields.

In an interferogram the reconstruction reference light beam is not quite parallel with the light beam transmitted through the hologram. This introduces a fixed difference in path length and phase, which reveals itself as parallel bars across the final photograph. These bars again represent a phase difference of 2π. The phase shifts of interest, those due to the sample, show up as displacements and distortions of the striped pattern in various regions of the photograph and, to a lesser extent, as changes in separation of the stripes. Figure 4b is an interference micrograph of the same cobalt particle. By the bending of the magnetic field lines in the central flat region, the direction of the magnetization can be determined.

The sensitivity of electron micrographs can be improved by a holographic phase-amplification technique (Ref 3) so that electron phase shifts as astonishingly small as $2\pi/50$ can be detected. Electron micrographs of deposited films now reveal atomic steps one atom in thickness. Another feature of holography has also proven useful. Figure 2 shows two images, the reconstructed "real" image on the opposite side of the hologram from the light source and its conjugate "virtual" image on the same side. The amplitudes of the two images are complex conjugates; the phase distributions are the same in magnitude but opposite in sign. This can be taken advantage of to double the phase shifts.

THE AHARONOV-BOHM EFFECT

We are conditioned by our training in classical physics to believe that forces are real and measurable; potentials are merely mathematical conveniences. From the inception of quantum mechanics it was evident that the Hamiltonian and the energy played the more central role, and yet the prejudice remained for 30 years that potentials could have no physical consequences in themselves. Then came Aharonov-Bohm (Ref 4): "We shall show that, contrary to the conclusions of classical mechanics, there exist effects of potentials on charged particles, even in regions where all the fields (and therefore the forces on the particles) vanish."

Here is the Aharonov-Bohm argument. Suppose a well-localized electron wave packet enters a Faraday cage. The electrical potential is initially zero, the Hamiltonian is H_0, and the wavefunction is ψ_0. When the electron is inside the cage the potential is changed to $-e\phi$. The wavefunction then becomes

$$\psi = \psi_0 e^{i\theta}$$

where θ is the altered phase and ψ is the solution of

$$(H_0 - e\phi)\psi = i\hbar\dot{\psi}$$

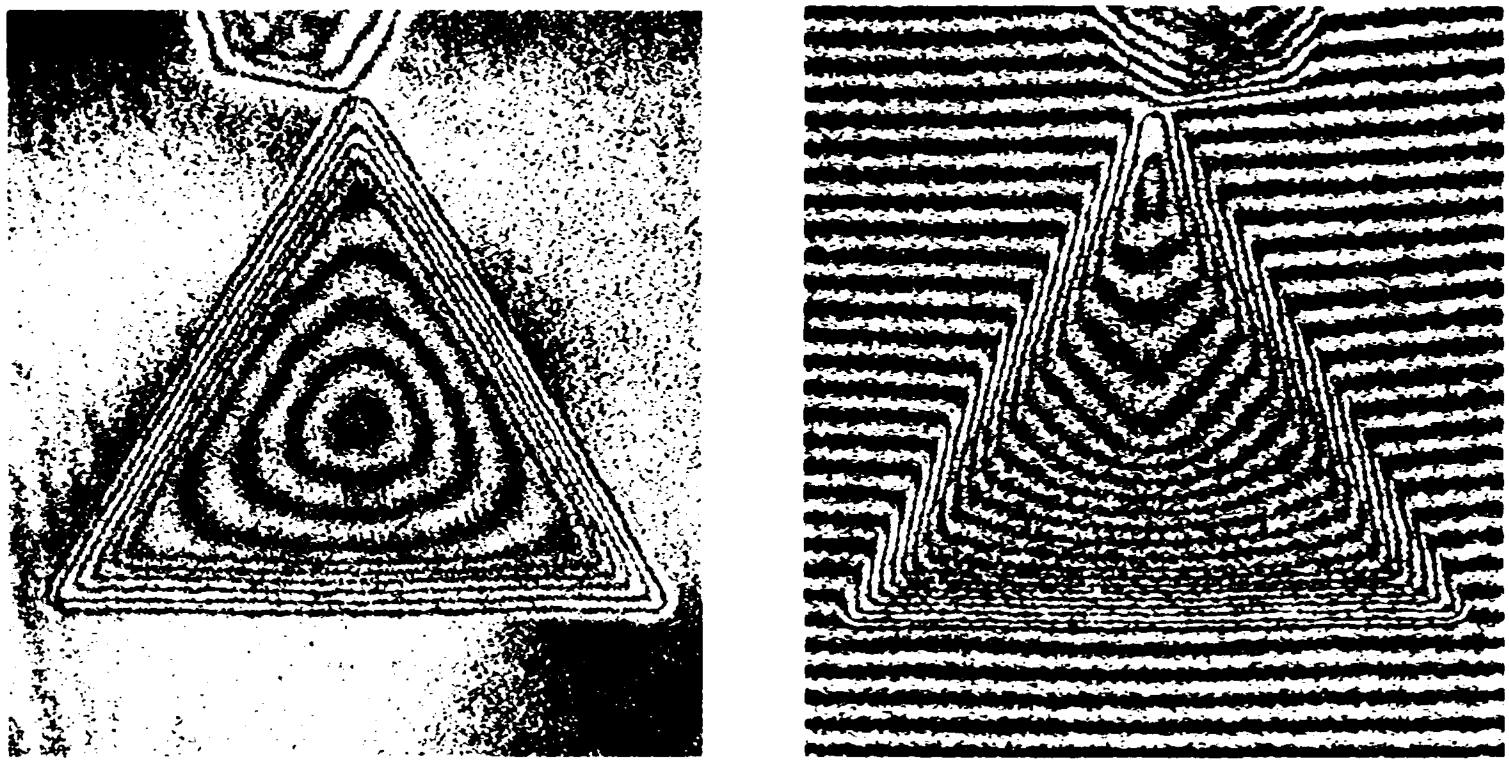
Clearly

$$\theta = \frac{e}{\hbar}\int_0^t \phi(t)\, dt$$

When there are both an electrical potential and a magnetic vector potential **A**, the phase shift of an electron is

$$\theta = -\frac{e}{\hbar}\left[\oint A \cdot dr - \int \phi(t)\, dt\right]$$

When there is only one path the phase is of no consequence. But now imagine the electron wave packet to be split into two branches, each of which enters a Faraday cage. Potentials ϕ_1 and ϕ_2 are then switched on, causing the two branches to differ in phase by an amount



(a) Contour map. The outer fringes are constant electrostatic potential lines. They are topographical projection lines, since their separation is proportional to the thickness gradient. The particle is uniformly bevelled along the edges and flat throughout the central region. The half dozen central lines and rings are magnetic field lines.

(b) Interferogram. Interferograms allow differentiation between fringe lines of electrical and magnetic origin, and allow determination of the direction of the magnetic field, or magnetization.

Figure 4. Interference micrographs of a triangular cobalt particle 1,000 Å on edge and about 550 Å thick.

$$\theta_1 - \theta_2 = \frac{e}{\hbar} \int_0^t [\phi_1(t) - \phi_2(t)]\, dt$$

In the recombined beam the electron then displays an interference pattern due to the potential difference.

The argument sounds leaky; one is incited to argue that the cause of the phase shift was the electromagnetic fields accompanying changing the voltages. But this cannot be the answer. Suppose that in each cage the potential is turned on after entry of the electron, held constant for some time t before re-emission, and then turned off. The phase difference is

$$\Delta\theta = \frac{e}{\hbar}(\phi_1 - \phi_2)\, t$$

and this depends on the length of time the potentials were kept on! The dialectic is reminiscent of the twin paradox.

The magnetic case is even more counterintuitive. Suppose there to be a solenoid stretching from $-\infty$ to $+\infty$ along the z axis. The solenoid is tightly wound, small in cross section, and carries a constant current. The magnetic field **B** is wholly internal to the solenoid and the lines of vector potential are circles in xy planes. In the z=0 plane a coherent charged beam is split to go on both sides of the solenoid and recombined. There will be an interference pattern in the wavefunction, even though the particle never entered the magnetic field. (But since interference depends on the difference in phases, the arbitrary additive constant in the electrical potential and the arbitrary gradient in the vector potential cancel out. Things are not as bad as they could be.)

The Aharonov-Bohm effect has provoked extensive literature (Ref 5,6) and some controversy. By Stokes' theorem

$$\oint \mathbf{A} \cdot d\mathbf{r} = \oint \mathbf{B} \cdot d\mathbf{a} = \Phi, \text{ the flux}$$

This has tempted numerous authors to argue that the effect depends on the flux, not the magnetic potential. One paper (Ref 7) denies the existence of the effect altogether.

The early experimental verification (Ref 5,6) was arguable. The experiments used finite solenoids or magnetized iron whisker, and one could not with total confidence exclude leakage magnetic fields (Ref 8). Another suggested (Ref 9) possible artifact was that the electron wavefunction penetrated the solenoid or whisker and was thus subject to the Lorentz force.

We now have the definitive experiment (Ref 5), and the Aharonov-Bohm effect is for real. Satisfyingly, the experiment also takes advantage of uniquely quantum mechanical phenomena—superconductivity and flux quantization.

PHASE, SUPERCONDUCTIVITY, AND FLUX QUANTIZATION

Tiny, thin toroids of permalloy between 10 and 20 μm in diameter are enclosed in niobium and this in turn is coated with copper. (This is, of course, not the fabrication process; see Reference 5.) Permalloy is a ferromagnet with a very large permeability. The magnetization lies in the toroid plane and circles around, closing on itself. The vector potential lies in planes normal to the toroid plane. Lines of **A** thread through the hole in the toroid and loop around outside, closing on themselves. When the toroids are perfectly circular no **B** lines escape from them. Room temperature electron interferograms reveal flux leakage in many cases, and these toroids are rejected. Another problem is encountered at low temperatures. One layer of niobium is evaporated on, and it frequently occurs that there are regions of incomplete contact between the upper and lower niobium layers--perhaps due to small oxide patches--forming tunneling junctions. Since Josephson curr nts vitiate flux quantization, such toroids are rejected. This still leaves a small number of perfect toroids. Copper is not a superconductor but has a high electrical conductivity. The copper covering guarantees that the electron cannot penetrate to the permalloy toroid. Niobium is a superconductor, with a transition temperature of 9.2 K. Since the many-electron superconducting wavefunction must be single valued, its phase can change only by an integral multiple of 2π in going around the cross section of the niobium-covered permalloy. Supercurrents will be induced in the niobium to loop in vertical planes through the hole in the toroid and around, creating an additional **B** field parallel to that in the permalloy due to the magnetization, such that the phase shift caused by the total flux integrates to an integral multiple of 2π. Thus the flux is quantized. Since two electrons couple together to condense into a Cooper pair in the superconducting state according to BCS theory, the flux is quantized in units of h/2e. When n fluxoids are present the flux is nh/2e.

CONCLUSIVE DEMONSTRATION OF THE AHARONOV-BOHM EFFECT

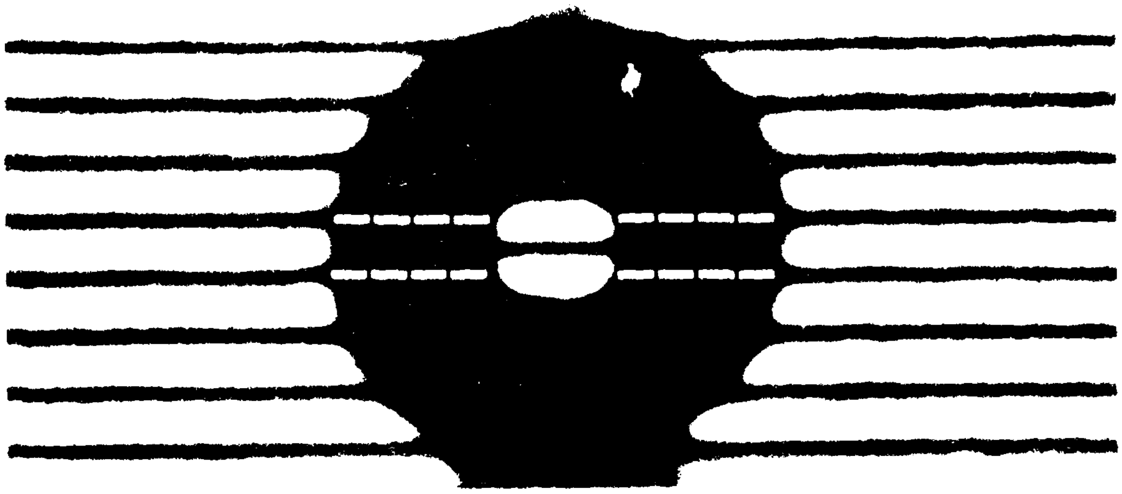
If an electron is then projected to be incident on the toroid, so that some of the electron wavefunction goes through the hole and some around the outside, between the two branches there will be a relative phase shift equal to $n\pi$ mod 2π. If n happens to be odd, the phase shift will be π, and the interior interferogram lines will be exactly halfway between the exterior ones. If n happens to be even, an interference micrograph will display no apparent shift of the interference lines inside the toroid relative to those outside. Figure 5 illustrates both cases.

Flux is quantized only in the superconducting state. Above the transition, when the niobium is normal, any amount of flux can traverse the toroid, and the phase shift is arbitrary. Figure 6 shows a toroid interferogram, first below the transition temperature of the niobium, and with an odd number of fluxoids in the permalloy. When the temperature is raised to 15 K the niobium is normal; the interference line inside the toroid is now no longer halfway between the outer lines. At room temperature the magnetization of the permalloy has dropped off, due to normal thermal fluctuations in the spin system, and there is a further shift in the fringes.

Return to the superconducting regime for a moment, and recall that there are conjugate phase shifts in the real and virtual images. Superposing these images doubles the phase shift. Whether n is odd or even, the phase shift is 0 mod 2π. The interferogram lines should then show no shift. This is observed. We think it is fair to say that the case for the Aharonov-Bohm effect is now compelling.

FINAL REMARKS

The inner subject of this article is phase in quantum mechanics. Potentials change the phase of the wavefunction of charged particles. Because the superconducting wavefunction must be single valued, flux is quantized. The superconducting wavefunction is correlated in phase across Josephson junctions. Electromagnetism is a gauge field theory and the Aharonov-Bohm effect can be viewed as evidence for the validity of such theories (Ref 10).



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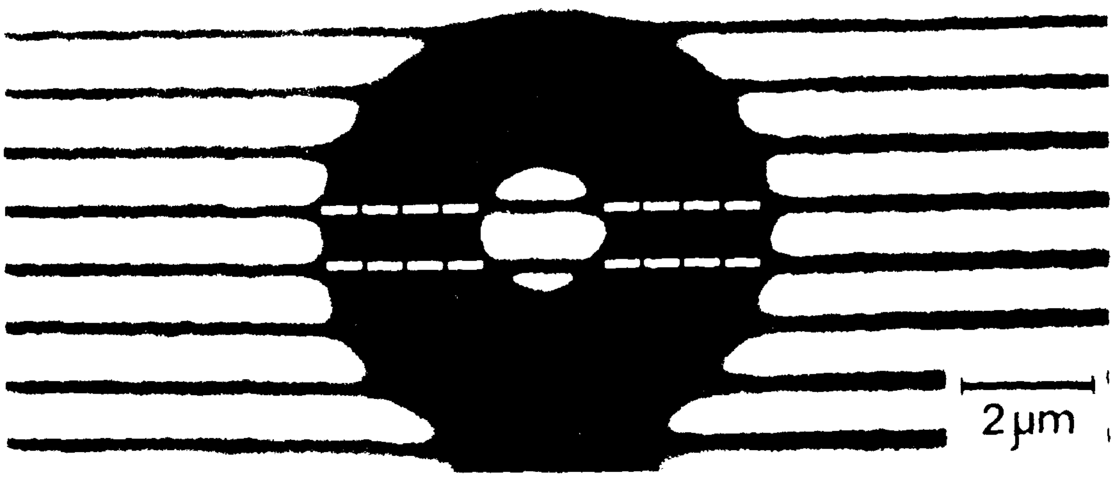
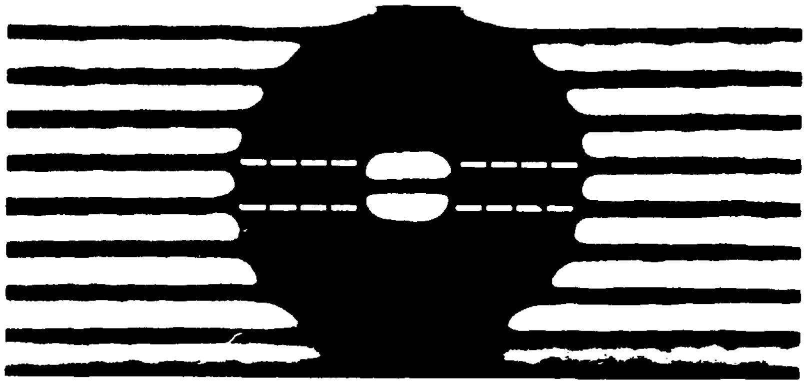
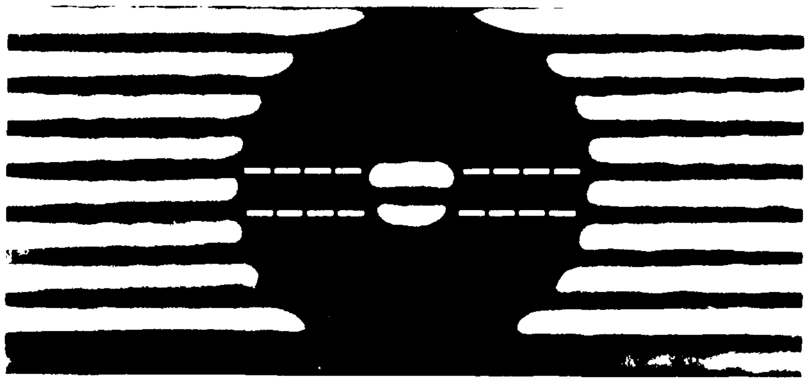


... are seen to restore the pattern.

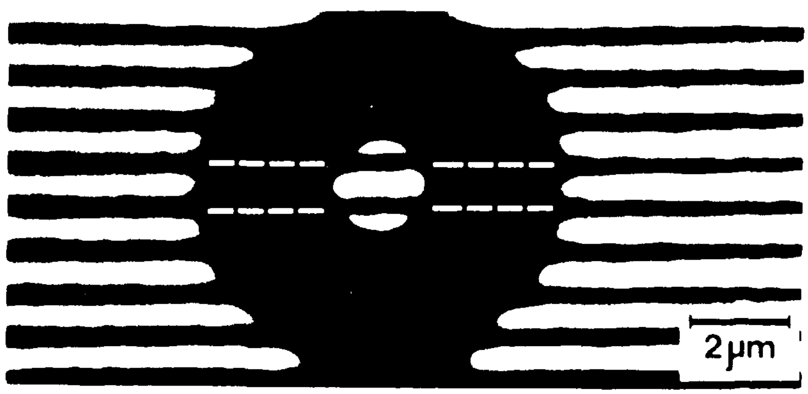
ONREF SCRIPT



(a) Below the superconducting transition temperature of niobium, flux is quantized. The toroid happens to have trapped an odd number of fluxoids, and the internal fringe is exactly halfway between the outer fringes.



(b) The temperature has been raised a little above the niobium superconducting transition temperature. There is now no quantization requirement, and the internal fringe is asymmetrically shifted.



(c) Raising the temperature to room temperature reduces the magnetization of the permalloy, and further shifts the fringe.

Figure 6. Interferogram of a toroid at several temperatures.

The quantum Hall effect and fluctuations in all the transport properties in submicron wires and rings are subject to the Aharonov–Bohm effect. Mesoscopic systems are rings or wires of such small dimension that an electron traverses the conductor before it loses phase memory. By the fluctuation–dissipation theorem (Ref 11), if the response of a system is dissipative under a driving force (resistance to current flow under impressed voltage), there must be spontaneous fluctuations in voltage and current (and conductance, even away from equilibrium). Now suppose the ring to be in a magnetic field. The requirement that the phase of the electron wave function be single valued imposes h/e (and sometimes h/2e) oscillations on the spontaneous fluctuations (Ref 12). Since only inelastic, not elastic, collisions cause loss of phase memory by the electron, the phase memory mean free path can be long, even up to a micron.

A recent development is the recognition of Berry phases.

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Akira Tonomura is a research physicist in the Advanced Research Laboratory of Hitachi Ltd. A graduate of Tokyo University, Dr. Tonomura worked on electron interferometry at Tübingen University, Germany, under Möllenstedt and returned to Japan to obtain his Ph.D. in physics at Nagoya University. In 1982 he was awarded the Nishina Memorial Prize and in 1987 the Asahi Prize for his work in electron holography and his demonstration of the Aharonov-Bohm effect.

INTERNATIONAL MEETINGS IN THE FAR EAST

1987-1994

Compiled by Yuko Ushino

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The Australian Academy of Science, the Japan Convention Bureau, and the Science Council of Japan are the primary sources for this list. Readers are asked to notify us of any upcoming international meetings and exhibitions in the Far East which have not yet been included in this report.

1987

Date	Title, Attendance	Site	For information, contact
October 5-8	The 5th International Workshop on Database Machines	Karuizawa, Japan	Professor M. Kitsuregawa, I.W.D.M. Secretariat c/o Inter Group Corporation, Akasaka Yamakatsu Building, 8-5-32 Akasaka, Minato-ku, Tokyo 107
October 5-9	IEEE Computer Society's 11th International Computer Software and Applications Conference *20-F400-J900**	Tokyo, Japan	c/o Information Processing Society of Japan 2-40-14 Hongo, Bunkyo-ku, Tokyo 113
October 5-9	The 4th Asian-Pacific Regional Meeting (IAU)	Beijing, People's Republic of China	Dr. Q.B. Li, Beijing Astronomical Observatory, Academia Sinica Beijing
October 6-9	IMACS/IFAC International Symposium on Modeling and Simulation of Distributed Parameter Systems 20-F50-J110	Hiroshima, Japan	Professor Tanehiro Futagami, Civil Engineering, Hiroshima Institute of Technology 725 Miyake, Itsukaichi-cho, Saeki-ku, Hiroshima 731-51
October 12-15	The 2nd International Conference and Exhibition of Biotechnology (BIO '87 Japan) 26-F200-J400	Osaka, Japan	Organizing Committee of BIO Japan c/o Osaka Convention Bureau, Osaka Chamber of Commerce and Industry 58-7 Uchihonmachi Hashizume-cho, Higashi-ku, Osaka 540

*Note: Data format was taken from the Japan International Congress Calendar published by the Japan Convention Bureau.

No. of participating countries
F: No. of overseas participants
J: No. of Japanese participants

Date	Title, Attendance	Site	For information, contact
October 12-16	The 12th International Conference on Atomic Collisions in Solids 20-F80-J160	Okayama, Japan	Professor Fuminori Fujimoto, Physics Section, College of General Education, University of Tokyo 3-8-1 Komaba, Meguro-ku, Tokyo 153
October 12-16	Chapman Conference on Plasma Waves and Instabilities in Magnetospheres and at Comets F100-J50	Miyagi, Japan	Faculty of Science, Tohoku University Aoba, Aramaki, Sendai 980
October 12-16	The 2nd International Symposium on Off-Flavours in the Aquatic Environment 20-F54-J58	Kagoshima, Japan	Faculty of Fisheries, Kagoshima University 4-50-20 Shimoarata, Kagoshima 890
October 12-18	The 2nd Japan-Korea Joint Symposium on Analytical Chemistry 2-F30-J50	Fukuoka, Japan	The Japan Society for Analytical Society 1-26-2 Nishi Gotanda, Shinagawa-ku, Tokyo 141
October 14-17	Tokyo Seminar on Macromolecule-Metal 10-F50-J150	Tokyo, Japan	Organizing Committee, Tokyo Seminar on Macromolecule-Metal Complexes c/o Ibaraki University, Bunkyo, Mito 310
October 15-16	Microoptics Conference '87	Tokyo, Japan	Professor Kenichi Iga, Program Cochair MOC '87, Tokyo Institute of Technology 4259 Nagatsuta, Midori-ku, Yokohama 227
October 18-24	International Towing Tank Conference (ITTC) 30-F100-J100	Kobe, Japan	Society of Naval Architects of Japan (SNAJ) Sempaku-Shinko Building, 8th Floor, 1-15-16 Toranomon, Minato-ku, Tokyo 105
October 20-23	International Conference on Quality Control--1987 Tokyo 45-F350-J400	Tokyo, Japan	Union of Japanese Scientists and Engineers 5-10-11 Sendagaya, Shibuya-ku, Tokyo 151

Date	Title, Attendance	Site	For information, contact
October 21-23	Sapporo International Computer Graphics Symposium 3-F24-J300	Sapporo, Japan	Sapporo International Computer Graphics Symposium Executive Committee Sapporo City Office Nishi 2-chome, Kita 1-jo, Chuo-ku, Sapporo 060
October 24-25	International Conference on Lasers	People's Republic of China	Professor Wang Zhi-Jiang, Shanghai Institute of Optics and Fine Mechanics P.O. Box 8211, Shanghai
October 25-28	The 5th International Symposium on Amyloidorsis 15-F80-J220	Hakone, Japan	Foundation for Advancement of International Science c/o Toneyama National Hospital, 5-1-1 Toneyama, Toyonaka, Osaka 560
October 26-29	The 2nd International Symposium on Transport Phenomena in Turbulent Flows 20-F100-J150	Tokyo, Japan	Department of Mechanical Engineering, University of Tokyo 7-3-1 Hongo, Bunkyo-ku, Tokyo 113
October 26-30	1987 Tokyo International Gas Turbine Congress	Tokyo, Japan	c/o Nissei Kogyo K.K. 2-5-10 Nishi-Shinbashi, Minato-ku, Tokyo 105
October 27-30	International Conference and Exhibition on Artificial Intelligence (AI '87 JAPAN) 20-F100-J400	Osaka, Japan	Inter Group Corporation Shohaku Building, 6-23 Chayamachi, Kita-ku, Osaka 530
October 30-November 1	Structural and Functional Aspects of Molecular Architecture of Proteins (Kyoto Bioscience Symposia IV) 10-F10-J90	Kyoto, Japan	Institute for Chemical Research Gokasho, Uji 611
November 2-4	The 6th Symposium of the Federation of Asian and Oceanian Biochemists 20-F280-J20	Karachi, Pakistan	Dr. A. Rahman, Department of Biochemistry, Jinnah Post-Graduate Medical Centre, Karachi
November 3-6	The 3rd International Photovoltaic Science and Engineering Conference 23-F150-J300	Tokyo, Japan	Japan Society of Applied Physics c/o Japan Convention Service, Inc. 2-2-1 Uchisaiwai-cho, Chiyoda-ku, Tokyo 100

1987

Date	Title, Attendance	Site	For information, contact
November 4-6	'87 International Symposium on Science and Technology of Sintering	Tokyo, Japan	Professor Shigeyuki Somiya, Sintering '87, Tokyo c/o Nikkan Kogyo Shimbun, Ltd., Planning Bureau, 8-10 Kudan Kita 1-chome, Chiyoda-ku, Tokyo 102
November 7-11	The 10th International Congress on Metallic Corrosion	Madras, India	Lois Baigée, National Research Council of Canada Ottawa ON K1A 0R6
November 9-12	The 19th Yamada Conference on Ordering and Organization in Ionic Solutions 10-F40-J100	Kyoto, Japan	Department of Polymer Chemistry, Kyoto University Yoshida-hommachi, Sakyo-ku, Kyoto 600
November 9-13	The 2nd International Conference on Refractories 6-F170-J270	Tokyo, Japan	Secretariat: The 2nd International Conference on Refractories c/o International Congress Service, Inc., Kasho Building, 2-14-9 Nihombashi, Chuo-ku, Tokyo 103
November 15-18	1987 Global Telecommunications Conference (GLOBECOM'87) 30-F500-J700	Tokyo, Japan	Secretariat: GLOBECOM'87 c/o KDD Research and Development Laboratories, 2-1-23 Nakameguro, Meguro-ku, Tokyo 153
November 22	The 3rd International Symposium on Natural and Industrial Arsenic 3-F3-J150	Kagoshima, Japan	Japanese Arsenic Scientist's Society c/o Kagoshima University 1-21-40 Korimoto, Kagoshima 890
November 25-27	The 18th Japan Conference on Radiation and Radioisotopes 30-F60-J600	Tokyo, Japan	Japan Atomic Industrial Forum, Inc. Toshin Building, 1-1-13 Shimbashi, Minato-ku, Tokyo 105
December 7-11	The 7th International Conference on Thin Films (ICTF-7)	New Delhi, India	Dr. Lalit Malhotra, Secretary, ICTF-7, Department of Physics, Indian Institute of Technology New Delhi, 110016
December 9-10	SEMI Technology Symposium '87 5-F30-J370	Tokyo, Japan	Semiconductor Equipment and Materials Institute 1-5-10-410 Roppongi, Minato-ku, Tokyo 106

1988

Date	Title, Attendance	Site	For information, contact
January 28-31	Royal Australian Chemical Institute, Division of Inorganic Chemistry, National Meeting (COMO 13)	Melbourne, Australia	Dr. P. Tregloan, Department of Inorganic Chemistry, University of Melbourne Parkville, Victoria 3052
February 2-5	The International Association of the Institute of Navigation (IAIN) Congress	Sydney, Australia	The Australian Institute of Navigation Box 2250, G.P.O., Sydney, New South Wales, Australia 2001
February 2-5	A Congress of the International Association of Institutes of Navigation	Sydney, Australia	Professor Günther Zade, World Maritime University P.O. Box 500, S-20124 Malmö, Sweden
February 22-26	Engineering Conference	Sydney, Australia	The Conference Manager, The Institution of Engineers, Australia 11 National Circuit, Barton, ACT 2600
February (tentative)	The 10th Australian Electron Microscopy Conference	(Undecided)	Secretariat: Australian Academy of Science GPO Box 783, Canberra, ACT 2601
March 1-3	International Forum on Fine Ceramics '88 Nagoya Japan 10-F100-J900	Nagoya, Japan	Secretariat: International Forum on Fine Ceramics c/o Japan Fine Ceramics Center 2-4-1 Mutsuno, Atsuta-ku, Nagoya 456
March 10-12	International Biotechnology Symposium '88 (tentative) 10-F100-J500	Nagoya, Japan	Organizing Committee of International Biotechnology Symposium c/o The Foundation of Chubu Science and Technology Center 2-17 Sakae, Naka-ku, Nagoya 460
March 14-16	International Symposium on Non-Equilibrium Solid Phase of Metals and Alloys F100-J200	Kyoto, Japan	Department of Metal Science and Technology, Faculty of Engineering, Kyoto University Yoshida-hommachi, Sakyo-ku, Kyoto 600
March 14-17	International Symposium on Non-Equilibrium Solid Phases of Metals and Alloys N.A.-F100-J200	Kyoto, Japan	Department of Metal Science and Technology, Faculty of Engineering, Kyoto University Yoshida-Hommachi, Sakyo-ku, Kyoto 600
March 22-25	International Symposium on Basic Technology for Future Industries (New Materials) 6-F15-J700	Kobe, Japan	c/o Agency of Industrial Science and Technology Ministry of International Trade and Industry 2-1-3 Kasumigaseki, Chiyoda-ku, Tokyo 100

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Date	Title, Attendance	Site	For information, contact
March 22-26	International Conference on Several Complex Variables, Kyoto 7-F15-J26	Kyoto, Japan	Research Institute for Mathematical Sciences, Kyoto University Oiwake-cho, Kita-Shirakawa, Sakyo-ku, Kyoto 606
April 4-12	The 4th International Conference on Aluminium Association (JLWA) 32-F100-J150	Tokyo, Japan	Japan Light Metal Welding and Construction Weldment Yura Building, 3-37-23, Kanda-Sakumacho, Chiyoda-ku, Tokyo 101
April 11-14	ISFNT International Symposium on Fusion Nuclear Technology 20-F150-J50	Tokyo, Japan	Nuclear Engineering Research Laboratory, Tokyo University Tokai-mura, Naka-gun, Ibaraki 319-11
April 13-15	The 21st JAIF Annual Conference 25-F250-J1,000	Tokyo, Japan	Japan Atomic Industrial Forum, Inc. Koshin Building, 1-1-13 Shimbashi, Minato-ku, Tokyo 105
April 19-23	International Conference on Nuclear Power Plant Water Chemistry—Operation Experience and Sophisticated Management Technology	(to be decided)	Japan Atomic Industrial Forum, Inc. Toshin Building, 1-1-23 Shimbashi, Minato-ku, Tokyo 105
April 26-May 3	The 3rd World Biomaterials Conference 15-F500-J500	Kyoto, Japan	Japan Society for Biomaterials c/o Institute for Medical and Dental Engineering, Tokyo Medical and Dental University, 2-3-10 Kanda-Surugadai, Chiyoda-ku, Tokyo 101
May 13-15	International Symposium on Advanced Thermal Spraying Technology and Allied Coatings 13-F50-J150	Osaka, Japan	High Temperature Society of Japan c/o Welding Research Institute of Osaka University 11-1 Mihogaoka, Ibaraki-shi, Osaka 567
May 16-20	The 4th International Conference on Metalorganic Vapor Phase Epitaxy	Hakone, Japan	Professor T. Katoda, Secretary, ICMOVPE IV c/o International Congress Service, Inc., Kasho Building 2F, 2-14-9 Nihombashi Chuo-ku, Tokyo 103
May 22-27	The 16th International Symposium on Space Technology and Science	Sapporo, Japan	The 16th International Symposium on Space Technology and Science, Sapporo Organizing Committee 4-6-1 Komaba, Meguro-ku, Tokyo 151

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Date	Title, Attendance	Site	For information, contact
May 25-27	The 5th International Microelectronics Conference (IMC 1988)	Tokyo, Japan	Dr. H. Hirabayashi, ISHM Japan Chapter 6-20-4 Hanakoganei, Kodaira-city, Tokyo 187
May 29-June 2	The 5th International Symposium on Halide Glasses	Susono, Japan	Professor Masayuki Yamane, Inorganic Materials, Faculty of Engineering, Tokyo Institute of Technology 2-12-1 Ookayama, Meguro-ku, Tokyo 152
May 30-June 3	MRS International Meeting on Advanced Materials 20-F600-J1,500	Tokyo, Japan	Organizing Committee for MRS International Meeting on Advanced Materials c/o Nikkan Kogyo Shimbun Ltd., Planning Bureau, 1-8-10 Kudan-kita, Chiyoda-ku, Tokyo 102
May 30-June 3	International Conference on Nuclear Data for Science and Technology 10-F100-J200	Mito, Japan	Japan Atomic Energy Research Institute Tokai-mura, Naka-gun, Ibaraki 319-11
June 5-10	The 6th International Conference on Surface and Colloid Science	Hakone, Japan	Division of Colloid and Surface Chemistry, The Chemical Society of Japan 1-5 Kanda-Surugadai, Chiyoda-ku, Tokyo 101
June 6-10	International Conference on Physical Metallurgy of Thermomechanical Processing of Steels and Other Metals 20-F100-J100	Tokyo, Japan	Nippon Tekko Kyokai 3rd Floor, Keidanren Kaikan, 1-9-4 Otemachi, Chiyoda-ku, Tokyo 100
June 7-10	International Conference on Precision Electro-magnetic Measurements (CPEM'88)	Tsukuba, Japan	The Society of Instrument and Control Engineers 1-35-28-303 Hongo, Bunkyo-ku, Tokyo 113
June 7-10	The 7th International Conference on Ion Implantation Technology (IIT'88)	Kyoto, Japan	Professor Isao Yamada, Ion Beam Engineering Experimental Laboratory, Kyoto University Sakyo, Kyoto 606
June 12-17	The International Conference on Ion Beam Modification of Materials (IBMM'88)	Tokyo, Japan	Professor Susumu Nanba, Faculty of Engineering Science, Osaka University 1-1 Machikaneyama-cho, Toyonaka-city, Osaka 560

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Date	Title, Attendance	Site	For information, contact
June 13-15	JSAP-MRS (Japan Society of Applied Physics-Material Research Society) International Conference on Electronic Materials	Tokyo, Japan	Professor Takeshi Kamiya, Faculty of Engineering, Tokyo University 7-3-1 Hongo, Bunkyo-ku, Tokyo 113
July 1-12	The 16th International Congress of Photogrammetry and Remote Sensing 48-F2,000-J2,600	Kyoto, Japan	Japan Society of Photogrammetry 601 Daiichi Honan Building, 2-8-17 Minami-Ikebukuro, Toshima-ku, Tokyo 171
July 12-15	The 6th International Conference on Ultrafast Phenomena 20-F200-J200	Shiga, Japan	The 6th International Conference on Ultrafast Phenomena Organization Committee c/o OPTO Marketing Service Ltd., Maenocho Heights 5-206, 6-10 Maenocho, Itabashi-ku, Tokyo 174
July 17-23	International Congress of Endocrinology 48-F2,000-J2,600	Kyoto, Japan	Japan Endocrine Society c/o Seirenkaikan, Kyoto Furitsu Medical University, Nishizume Konjinbashi, Kamigyo-ku, Kyoto 602
July 18-22	International Symposium on Scale Modeling	Tokyo, Japan	Secretariat: c/o The Japan Society of Mechanical Engineers, Sanshin Hokusei Building, 2-4-9 Yoyogi, Shibuya-ku, Tokyo 151
July 18-22	1988 XVI International Conference on Quantum Electronics 30-F300-J700	Tokyo, Japan	Optoelectronic Industry and Technology Development Association No. 20 Mori Building, 2-74 Nishi-shimbashi, Minato-ku, Tokyo 105
July 25-30	International Conference on Clustering Aspects in Nuclear and Subnuclear Systems 31-F150-J150	Kyoto, Japan	Dr. K. Tanaka, Faculty of Science, Hokkaido University 5-chome, Kita 10-jo, Kita-ku, Sapporo 060
August 1-5	The 10th Congress of the International Ergonomics Association	Sydney, Australia	Ergonomics Society of Australia and New Zealand, Science Centre 35-43 Clarence Street, Sydney, NSW 2000
August 1-6	The IUPAC 32nd International Symposium on Macromolecules 50-F600-J1,200	Kyoto, Japan	The Society of Polymer Science, Japan 5-12-8 Ginza, Chuo-ku, Tokyo 104

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Date	Title, Attendance	Site	For information, contact
August 2-6	The 9th World Conference on Earthquake Engineering 59-F800-J2,000	Tokyo, Jappan	Secretariat: The 9th SCEE Steering Committee c/o Association for Earthquake Disaster Prevention 5-26-20 Shiba, Minato-ku, Tokyo 108
August 14-19	The 10th International Congress on Rheology	Sydney, Australia	R. I. Tanner, Department of Mechanical Engineering, University of Sydney NSW 2006
August 15-17	International Federation of Automatic Control Symposium	Melbourne, Australia	Conference Manager, The Institution of Engineers, Australia 11 National Circuit, Barton, ACT 2600
August 15-17	Electrical IFAC Conference	Melbourne, Australia	Conference Manager, The Institution of Engineers, Australia 11 National Circuit, Barton, ACT 2600
August 15-19	The 3rd International Phycological Congress	Melbourne, Australia	Dr. M. N. Clayton, Botany Department, Monash University Clayton, Victoria 3168
August 16-19	The 7th International IUPAC Symposium on Mycotoxins and Phycotoxins 38-F100-J200	Tokyo, Japan	Japan Association of Mycotoxicology, Science University of Tokyo c/o Science University of Tokyo, 12 Fungagawara-machi, Ichigaya, Shinjuku-ku, Tokyo 160
August 21-26	International Geographical Congress	Sydney, Australia	Secretariat: Australian Academy of Science GPO Box 783, Canberra, ACT 2601
August 22-26	The 5th Australia-New Zealand Conference on Geomechanics	Sydney, Australia	Conference Manager, The Institution of Engineers, Australia 11 National Circuit Barton, ACT 2600
August 30-September 2	The 5th International Conference on Molecular Beam Epitaxy 15-F150-J400	Sapporo, Japan	Japan Society of Applied Physics c/o Department of Physical Electronics, Tokyo Institute of Technology 2-12-1, Oh-okayama, Meguro-ku, Tokyo 152
September 5-8	The 1st International Conference on Computational Methods in Flow Analysis F250-J300	Okayama, Japan	Okayama University of Science 1-1 Ridaicho, Okayama 700

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September 19-22	The 29th International Conference on the Biochemistry of Lipids 39-F100-J200	Tokyo, Japan	Secretariat: The 29th International Conference on the Biochemistry of Lipids c/o Department of Psychological Chemistry and Nutrition, Faculty of Medicine, University of Tokyo 7-3-1 Hongo, Bunkyo-ku, Tokyo 113
September 20-22	The 4th Japanese-German Joint Seminar on Non-destructive Evaluation and Structural Strength of Nuclear Power Plant 1-F30-J70	Kanazawa, Japan	Japan Atomic Energy Research Institute Tokai Establishment Tokai-mura, Naka-gun, Ibaraki 319-11
October 17-20	The 9th International Conference on Pattern Recognition	Beijing, People's Republic of China	9 ICPR Secretariat: Chinese Association of Automation P.O. Box 2728, Beijing
October 24-26	The 1st International Conference New Diamond Forum	Tokyo, Japan	Secretariat: International Congress Service, Inc. Kasho Building 2F, 2-14-9 Nihonbashi, Chuo-ku, Tokyo 103
October 24-28	The 3rd International Conference on Surface Engineering	Tokyo, Japan	Cotec Corporation Sankocho Building 5-17-14 Shinjuku, Shinjuku-ku, Tokyo 160
November 2-5	International High-Performance Vehicle Conference	Shanghai, People's Republic of China	Ship Design Committee CSNAME P.O. Box 3053, Shanghai
November 14-18	1988 Annual Meeting of the International Society for Interferon Research 35-F300-J500	Kyoto, Japan	The 5th ISIR Organizing Committee c/o Inter Group Corporation Shohaku Building, 6-23 Chayamachi, Kita-ku, Osaka 530
November 19-26	The 13th International Diabetes Federation Congress 20-F80-J120	Sydney, Australia	Professor J. R. Turtle, Professor of Medicine Department of Endocrinology, University of Sydney NSW 2006

1989

Date	Title, Attendance	Site	For information, contact
April 3-5	International Symposium for Electromachining 16-F100-J300	Nagoya, Japan	Institute of Industrial Science, University of Tokyo 7-22-1 Roppongi, Minato-ku, Tokyo 106
April 10-13	The International Symposium for Electromachining 15-F100-J300	Undecided	The Institute of Electrical Engineers of Japan Gakkai Center Building, 2-4-16 Yayoi, Bunkyo-ku, Tokyo 113
April 18-21	The 2nd Asian Fisheries Forum 30-F150-J150	Tokyo, Japan	Secretariat: The 2nd Asian Fisheries Forum c/o Faculty of Agriculture, Tokyo University 1-1-1 Yayoi, Bunkyo-ku, Tokyo 113
July 2-7	XXVII International Conference on Coordination Chemistry	Brisbane, Australia	Professor Clifford J. Hawkins, Department of Chemistry, University of Queensland Saint Lucia, Brisbane, Queensland 4067
July	The 4th International Organization of Plant Biosystematists (IOPB) Symposium 20-F,J250	Kyoto, Japan	IOPB Symposium c/o Department of Botany, Faculty of Science, Kyoto University Kitashirakawa Oiwake-cho, Sakyo-ku, Kyoto 606
August 13-18	Solar Energy Congress Tokyo 1989 40-F600-J400	Tokyo, Japan	Japanese Section of International Solar Energy Society 322 San Patio, 3-1-5 Takada-no-baba, Shinjuku-ku, Tokyo 160
August 27-September 1	The 5th International Symposium on Microbial Ecology (5th ISME) 73-F600-J600	Kyoto, Japan	Japanese Society of Microbial Ecology c/o Inter Group Corporation 8-5-32 Akasaka, Minato-ku, Tokyo 107
September 5-8	Solar World Congress 1989 60-F600-J400	Kobe, Japan	Japanese Section of International Solar Energy Society, Japan Solar Energy Society 322 San Patio, 3-1-5 Takada-no-baba, Shinjuku-ku, Tokyo 160
September 8-10	1989 International Symposium on Electromagnetic Compatibility 20-F150-J350	Nagoya, Japan	Secretariat: International Symposium on Electromagnetic Compatibility c/o Department of Information and Computer Sciences, Toyohashi University of Technology 1-1 Tenpaku-cho, Aza-Hibarigaoka, Toyohashi, Aichi 440

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October 3-5	The 10th Meeting of World Society for Stereotactic and Functional Neurosurgery 20-F200-J300	Maebashi, Japan	Department of Neurosurgery, Gumma University, School of Medicine 3-39 Showa-machi, Maebashi 371
October (tentative)	Specialty Electric Conference	Sydney, Australia	Conference Manager, The Institution of Engineers, Australia 11 National Circuit, Barton, ACT 2600
1989 (tentative)	International Conference Evaluation of Materials Performance in Severe Environments-Evaluation and Development of Materials in Civil and Marine Uses 20-F80-J120	Japan (undecided)	International Conference Secretariat, Conference and Editorial Department, Iron and Steel Institute of Japan 1-9-4 Otemachi, Chiyoda-ku, Tokyo 100
1989 (tentative)	International Conference on Zinc and Zinc Alloy Coated Sheet Steels 20-F50-J150	Japan (undecided)	International Conference Secretariat, Conference and Editorial Department, Iron and Steel Institute of Japan 1-9-4 Otemachi, Chiyoda-ku, Tokyo 100

1990

Date	Title, Attendance	Site	For information, contact
May 19-26	The 27th International Navigation Congress 60-F500-J500	Japan (undecided)	Japan Organizing Committee for 27th International Navigation Congress 2-8-24 Chikko, Minato-ku, Osaka 552
July (tentative)	The 10th International Congress of Nephrology 10-F1,000-J4,000	Osaka, Japan	Japanese Society of Nephrology c/o 2nd Department of Internal Medicine, School of Medicine, Tokyo 173
August 21-29	International Congress of Mathematicians	Kyoto, Japan	Research for Mathematical Sciences, Kyoto University Kitashirakawa Oiwake-cho, Sakyo-ku, Kyoto 606
September (tentative)	The 15th International Congress on Microbiology 57-F2,500-J2,500	Osaka, Japan	Preliminary Committee of International Congress of Microbiology c/o JTB Creative Inc., Daiko Building, 3-2-14 Umeda, Kita-ku, Osaka 530

1990

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1990 (tentative)	The 6th International Conference on the Science and Technology of Iron and Steel 50-F300-J500	Japan (undecided)	International Conference Secretariat and Editorial Department, Iron and Steel Institute of Japan 3F, Keidanren Kaikan, 1-9-4 Otemachi, Chiyoda-ku, Tokyo 100
1990 (tentative)	Chemeca 1990 Applied Thermodynamics	New Zealand	Conference Manager, The Institution of Engineers, Australia 11 National Circuit, Barton, ACT 2600

1991

Date	Title, Attendance	Site	For information, contact
August (tentative)	The 16th International Conference on Medical and Biological Engineering 45-F600-J900	Kyoto, Japan	ME Division, Kawasaki Medical School 577 Matsushima, Kurashiki City, Okayama 701-01
August (tentative)	International Congress on Medical Physics 45-F600-J900	Kyoto, Japan	National Institute of Radiological Science 4-9-1 Anagawa, Chiba 260

1992

1993

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1993 (tentative)	International Federation of Automatic Control Congress	Sydney, Australia	Conference Manager, The Institution of Engineers, Australia 11 National Circuit, Barton, ACT 2600

1994

Date	Title, Attendance	Site	For information, contact
Tentative	XXX International Conference on Coordination Chemistry	Kyoto, Japan	Professor Hitoshi Ohtaki, Department of Electronic Chemistry, Tokyo Institute of Technology at Nagatsuta 4259 Nagatsuta-cho, Midori-ku, Yokohama 227

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